THE GEOLOGY OF THE AREA AROUND WHITHORN, WIGTOWNSHIRE.

by

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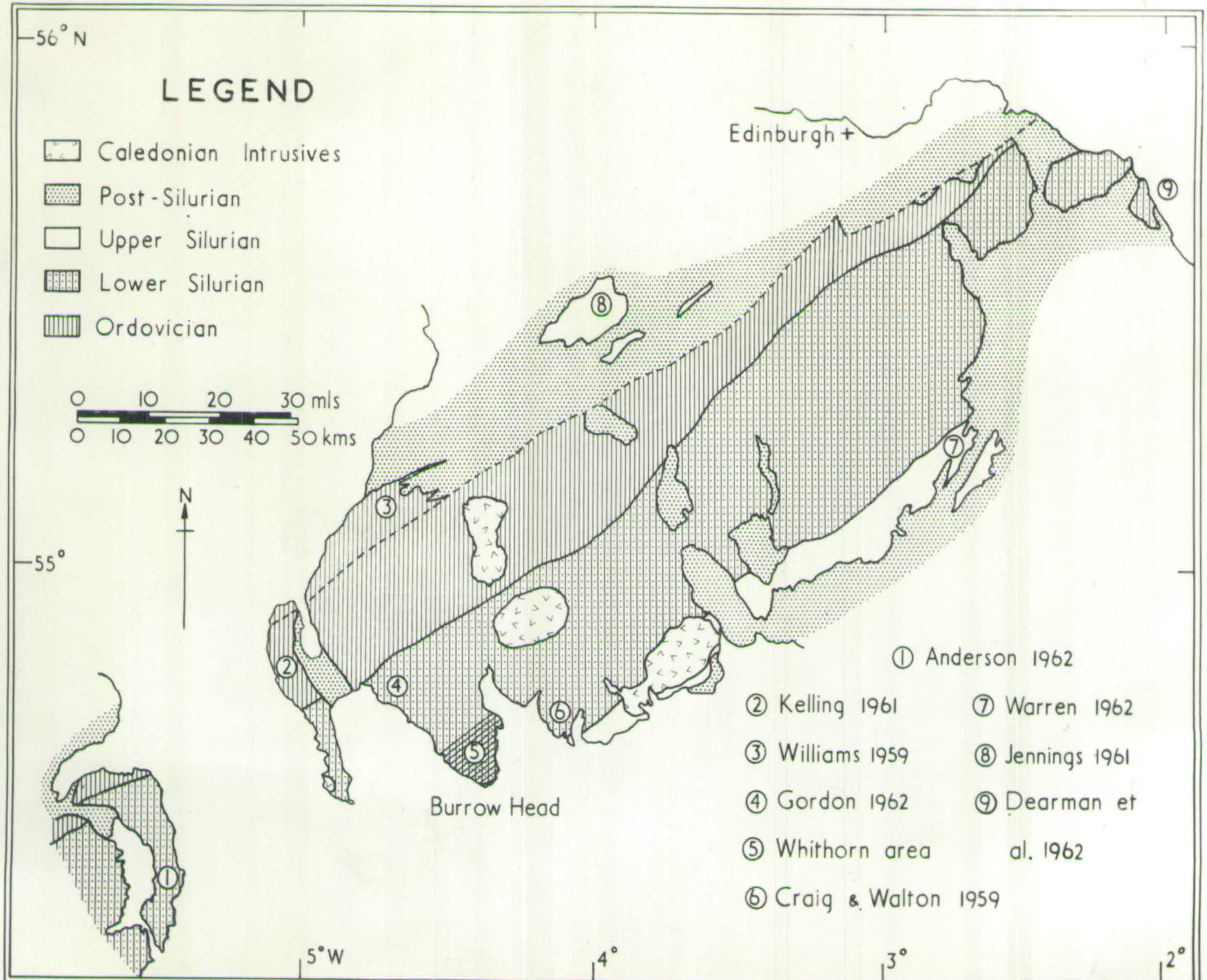


FIG. 2

Map showing the location of the Whithorn area, and other areas referred to in the text.

INTRODUCTION

The area studied is a promontory which covers about 50 square miles of south-east Wigtownshire, with Burrow Head at its extremity, and is located as shown in Fig.2. The whole of the east coast and about a third of the south-west coast is excellently exposed in cliffs and rocky foreshores. The remainder of the south-west coast is mantled by glacial deposits, but the line of pre-glacial sea cliffs provides quite good exposure. Inland outcrop is very variable, and consists mainly of glaciated knolls separated by drift-filled valleys. Because of the steep sides of the knolls, and the usually steep dip, the beds thus exposed are subject to outward creep, which makes structural data obtained from inland outcrop somewhat unreliable. The area has been mapped inland on a scale of 6" to the mile, while the coast has been covered on a 25" scale. Additional structural information has been obtained from aerial photographs.

The only previously undertaken general investigation of the area is that of Peach and Horne (1899). They obtained Wenlock graptolites at Burrow Head (p.551,2) and briefly described the folded Hawick strata further north (p.551). Peach and Horne also give a detailed bibliography of all earlier work concerned with various aspects of Southern Uplands geology.

Read (1926) has investigated the petrography of the lamprophyre dykes of Wigtownshire, including the present area. The dykes have also been re-classified for the 1923-1925 printing of H.M. Geological Survey's sheets 2 and 4, which cover the area.

Charlesworth (1926) has given a detailed account of the glacial geology of the area.

All structural information is expressed in the text in terms of three-figure true bearings and inclinations below the horizontal. Thus an axial plane inclined at 80° towards the north-west is written: 80°N 045, and an axis plunging 20° to the north-east: plunge 20° 045. Figures given in brackets after localities are 6-figure grid references taken from the Ordnance Survey 1" sheet (80) of Kirkcudbright.

STRATIGRAPHY

1. The stratigraphical relations of the Hawick and Riccarton Beds.

H.M. Geological Survey of Scotland distinguished two groups of rocks within the area: a southern group, the Riccarton Beds, and a northern group, the Hawick Rocks (Peach and Horne 1899). The former were identified as Wenlock in age by the finding of fossils diagnostic of the zone of *Cyrtograptus murchisoni*. The Hawick Rocks were somewhat doubtfully assigned to the Upper Valentian (or U. Llandoverian) for three reasons. Firstly, the primary red beds of the Hawick rocks were correlated with similar strata found in the U. Valentian (Tarannon) beds of the Lake District. Secondly, the southward dipping contact between the Hawick and Riccarton beds was taken to be a normal (i.e. not inverted) sedimentary one, which indicated that the Hawick Rocks were pre-*murchisoni* in age. Thirdly, the collection of Valentian graptolites including *Monograptus exiguus* from isolated inland localities well to the north of the main Hawick outcrop (eg. Whauphill and Baldoon Mains railway cuttings: Peach and Horne 1899, p.215) was accepted as evidence of Valentian age for all the intervening strata. These localities have been revisited, but careful search has not revealed the recorded fossiliferous beds. Although the railway cuttings are still in use (1962), they have probably become partly overgrown since they were originally investigated.

Despite considerable renewed interest in recent years, three problems concerning the Hawick Rocks remain: their age, their relation to the Riccarton Beds, and the definition of their northern limit.

Craig and Walton (1959) have challenged the view that the Hawick rocks are older than the Riccarton Beds. On the evidence of "way-up" criteria they suggest that the Hawick/Riccarton boundary is an inverted conformable one, so that the Hawick Rocks are younger than the Riccarton Beds. They show that the Hawick Rocks continue to get younger to the north-west and postulate faults with great vertical throws to account for the fact that older rocks (Lower Silurian and Ordovician) are eventually found further north. Craig and Walton also state that the Hawick/Riccarton boundary at Ross and Fauldbog Bays (Kirkcudbrightshire, see Fig.2) is sufficiently well-exposed to rule out the possibility of any but minor faults (Craig and Walton 1959, p.214).

This statement cannot be upheld, however, for the coast at these localities is low-lying and is interrupted by beach-filled inlets; the rocks are discoloured and show other evidence of tectonic activity. The same may be said of the exposure of the boundary on the east side of Kirkcudbright Bay, where again the occurrence of a major fault is not unlikely. In fact, the only complete and three-dimensional exposures of the Hawick/Riccarton boundary are to be found on the cliffs east and west of Burrow Head.

To the west of Burrow Head the boundary is a fault separating Hawick strata with red beds to the north from Riccarton beds containing graptolitic shales to the south; there is no interbanding of red and graptolitic strata. The dislocation zone of the fault is about four yards wide, (Plate 12B) and does not form a topographical feature; it could easily have been hidden by a small discontinuity in the exposure. The boundary reaches the east coast at Thief's Hole (464344), and there takes the form of a fault complex which has sliced up the rocks adjacent to the boundary, introducing small pieces of Hawick strata into the main Riccarton outcrop, and vice versa.

The presence of a larger tectonic slice of Riccarton Beds ¼ mile to the north across steeply dipping Hawick strata (Fig.1) indicates that the steep faults bounding this slice must have had a considerable dip-slip displacement. It is suggested that tectonic slicing of this sort may be responsible for the apparent interbedding of Hawick and Riccarton strata observed in Fauldbog Bay by Craig and Walton (1959, p.214).

Warren (1962) accepts the view of Craig and Walton that the Hawick/Riccarton boundary is an inverted sedimentary one, although it is not exposed in the area south of Hawick, which he studied (see Fig.2). He also agrees that the Hawick Rocks show a continued upward sequence when traced north of the boundary, but presents palaeontological evidence that the Riccarton Beds decrease in age towards the south. Warren therefore suggests that the most northerly group of the Riccarton Beds, which he terms the Stobs Castle Beds, are the oldest rocks in his area, and that the Hawick Rocks are facies equivalents of the remaining Riccarton strata.

Warren's acceptance of a conformable Hawick/Riccarton boundary is based on local successions in which red beds are said to occur with graptolitic shales in a straightforward sequence which excludes the possibility of faulting. The present author has visited the area around Stobs Castle, and was unable to find such a succession. However, if interbedding of red beds and graptolitic (Riccarton) beds can be undoubtedly demonstrated, this will not constitute proof of Hawick/Riccarton conformity, but will merely show that red beds were deposited in Riccarton times.

Despite lack of exposure, Warren denies the existence of a fault between the Riccarton and Hawick beds on the grounds that it would exhibit considerable topographical expression if it were present, (Warren,1962, pp 26-7). This argument is invalidated by other references to major faults in the Hawick area, for instance the Hyndlee Fault (Warren, 1962, p.352):

"Although a major dislocation, there is little direct evidence of its existence".

and the Wormscleuch Fault (p.353):

"...the evidence for this fault is largely non-existent".

The relevance of the Burrow Head Fault is also discounted by Warren (1962, p.27):

"A high angle strike fault between the Hawick and Riccarton group has been observed by the writer at Burrow Head, Wigtownshire, but the Riccarton group here is devoid of red mudstones and cannot therefore be correlated with the Stobs Castle Beds".

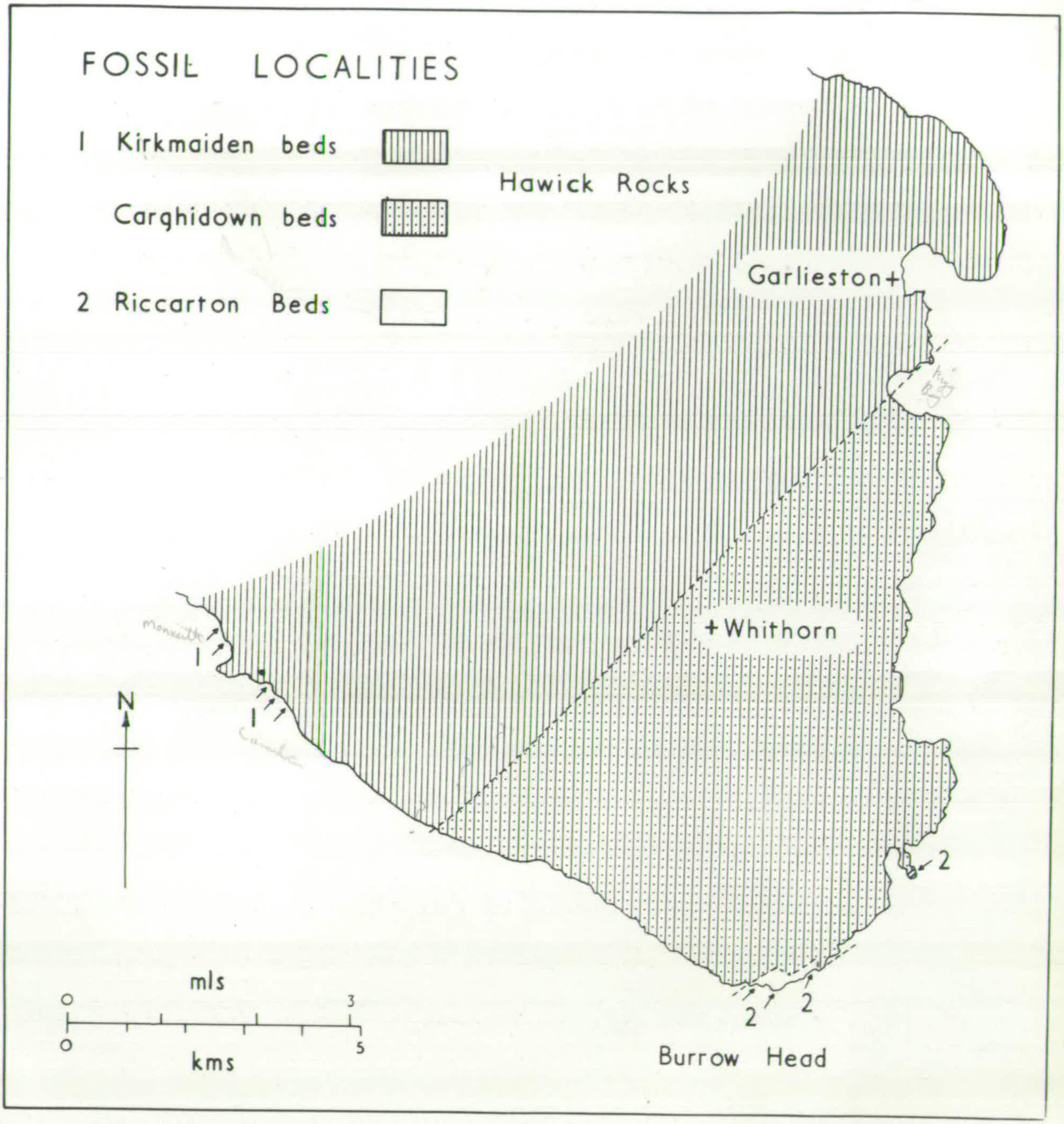
This statement is quite untrue, since the fauna of the Riccarton Beds at Burrow Head is precisely the same as that of the Stobs Castle Beds. It is therefore suggested that the apparent interbedding of red and graptolitic horizons observed in the Stobs Castle Beds by Warren may be due to the introduction of tectonic slices of Hawick strata into the succession.

As described elsewhere (pp.15,16), fossils which Dr. I. Strachan ascribes to the Upper Valentian have been found on the east coast between Cairndoon (375388) and Monreith (358407), (Fig.3). Although part of the coastal exposure between Cairndoon and Burrow Head has been obscured by drift, there remains sufficient to show that no different sedimentary types enter the sequence between these two points. The continuous exposure of the east coast from Burrow Head to Innerwell confirms this, and it is therefore assumed that the southern Hawick rocks underlie the fossiliferous (U. Valentian) horizons to the north, and are therefore older than the Riccarton Beds of Wenlock age. Part of the argument on which this conclusion is based concerns the succession within the Hawick Rocks, a discussion of which follows.

2. Stratigraphical divisions within the Hawick Rocks.

A simple stratigraphical division may be made on the presence or absence of primary red beds. In the southern part of the Hawick outcrop they are relatively abundant and thick. Abundance and thickness both decrease northward, until at Rigg Bay (480450) the last thin red bed is found on the east coast. Admittedly it is difficult to locate this horizon accurately since thin red beds might be masked by secondary iron staining,

FIG. 3



FOSSIL LOCALITIES
1 Kirkmaiden beds
Carghidown beds
2 Riccarton Beds
Hawick Rocks
Garlieston+
+Whithorn
Monreith
1
1
N
2
2
2
Burrow Head
mls
0
3
0
5
kms

which is widespread in the north-east corner of the area. However, the equivalent exposure on the west coast, i.e. between Cairndoon and Monreith is free of secondary reddening, and lacks any vestige of primary red beds. In every other respect the rocks of the northern part of the area are similar to those of the southern Hawick outcrop, and there seems to be little reason for defining the northern boundary of the Hawick rocks at this point. The rocks with and without primary red beds are therefore considered to be sub-divisions of the Hawick rocks, and are termed the Carghidown beds and the Kirkmaiden beds respectively. Limited exposure inland and on part of the west coast make it impossible to locate this boundary accurately; it can only be extrapolated across country parallel to the regional strike (Fig.3).

It is noteworthy that the Carghidown beds do not reappear as one passes from south to north, although local repetition of strata does occur through folding and faulting. From this it can be inferred that the numerous faults observed are not affecting the stratigraphical succession to any great extent. Thus the northward direction of upward sequence established from the disposition of folds and "way-up" criteria is not effectively countered by southerly downthrow on strike faults within the Hawick outcrop. Hence the conclusion follows that the Hawick rocks adjacent to the Riccarton boundary underlie the Upper Valentian strata, and must therefore be older than the Riccarton Beds.

Other stratigraphical divisions of the Hawick Rocks may be set up on the percentages of quartz obtained by micrometric analyses of the greywackes (pp.122-7). Thus three members have been established: two quartz-rich members to the north and south, separated by a quartz-poor member in the intermediate position. The northern quartz-rich member may be distinguished from the southern quartz-rich one by the absence of primary red beds, but the boundary marking the northern limit of red beds falls in the middle of the quartz-poor member. Some difficulty has been experienced in the tracing of these members across country on account of the comparative rarity of greywackes sufficiently coarse-grained and free from diagenetic effects, (Fig.25).

3. The northern boundary of the Hawick Rocks.

The term 'Hawick Rocks' was introduced in 1871 by Lapworth and Wilson, but no satisfactory definition was given. Recent studies of the stratigraphical position of the Hawick Rocks have been concerned with their relation to the Riccarton Beds (Craig and Walton 1959, Warren 1962). At present, the nearest approach to a definition of their northern limit is that given by Peach and Horne, (1899, p.57), who divide the Tarannon Rocks of the Central Belt in descending order as follows:

3. Grey, green and red shales, brown flagstones, and yellow-crusted greywackes with occasional grits (Hawick Rocks).
2. Massive grits and greywackes with local bands of conglomerate, with grey, green, and red shales

(Queensberry Grits).

1. Brown flagstones, green and grey shales and mudstones (Abbotsford Flags).

Thus it would appear that the important criterion for the location of the northern limit of the Hawick Rocks is the appearance of coarse-grained massive strata in the underlying Queensberry Grits.

Any attempt to define this northernlimit in the Whithorn area must be tentative, since inland exposure north-west of a line between Monreith and Orchardton (458498) is poor, and coastal exposure is entirely lacking as far as Garheugh Port on the west coast, 7 miles across the strike. The Garheugh rocks have been studied by Gordon (1962), who defined the Garheugh Formation on petrological grounds, and considered it to be equivalent to the Queensberry Grits (Gordon, Table 1, p.4, and p.12). The greywackes of the Garheugh Formation are much coarser than those of the Hawick Rocks, and also differ in colour, being greenish, as opposed to the brownish-grey of Hawick greywackes. These features usually enable one to distinguish them in the field. In thin section the Garheugh greywackes contain a higher proportion of quartz fragments than do the Hawick greywackes.

Gordon traces the Garheugh Formation as far as Mochrun Fell, across an inlier of older rocks (including Ordovician strata) at Drumblair. The present author has traversed the upland region between Mochrum Fell and Monreith, and found that rocks of Garheugh type may be followed south-eastward across the strike as far as outcrop will permit. This suggests that the boundary between the Hawick and Garheugh rocks occurs in the unexposed belt which lies between one and two miles north-west of the Monrieth-Orchardton line.

The boundary is almost certainly faulted, since the beds become younger to the north-west, whereas the rock groups are older when traversed in the same direction, a situation analogous to the Hawick/Riccarton relations. The suggested location of the Hawick/Garheugh boundary would place the fossil localities at Whauphill and Baldoon Mains (p. 3).within the Garheugh Formation (assuming no large-scale lateral displacement of the boundary). The important zonal fossil found at both localities is *Monograptus exiguus*, which indicates that the Garheugh Formation comes within the lower part of the Upper Valentian. Thus a tentatively revised stratigraphical table of the Silurian Rocks between Burrow Head and Glenluce reads as follows (partly after Gordon, 1962):

Riccarton Beds:	*Cyrtograptus murchisoni*	L. Wenlock	
Fault			
H awick Rocks:	*Monograptus crenulatus* *M.griestonensis*	U. Gala	U. Valent.
Fault			
Garheugh Formation:	*M. crispus* *M. turriculatus*	L. Gala	
Fault			
Kilfillan Formation:	Uncertain	L. Valentian (Birkhill).	

PALAEONTOLOGY

With the exception of dark grey graptolitic siltstones occurring in the Riccarton Beds, the rocks of the area are extremely poor in fossils. The coarse-grained sediments appear to be completely barren.

1. Riccarton Beds.

The fauna of the grey siltstones at Burrow Head has been described by the Geological Survey, and ascribed to the Wenlock zone of *Cyrtograptus murchisoni* (Peach and Horne, 1899, p. 552). The fossils listed include the following:

Cyrtograptus murchisoni *

C. carruthersi

Monograptus flemingi

M. priodon

M. vomerinus

Retiolites geinitzianus

In the present work, some of the more important fossils found at Burrow Head have been identified by Dr. I. Strachan as follows:

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* Described on Sheet 2 as *Cryptograptus murchisoni* in error.

Cyrtograptus aff. insectus (Boucek) or centrifugus (Boucek).

C. (?) pulchellus

Monograptus vomerinus, (?) var. basilicus

Retiolites geinitzianus

Dr. Strachan states that the cyrtograptids identified by the Survey as C. murchisoni are in fact C. insectus or C.-centrifugus, which are both of the C. murchisoni group, and come from the same horizon as that species. Thus the Survey's conclusion that these rocks belong to the basal Wenlock zone of C. murchisoni is confirmed. No variation in fauna was found across the limited outcrop of Riccarton Beds on Burrow Head.

Another small outcrop of the Riccarton Beds has been recognised at the end of Isle Head, near the village of Isle of Whithorn (Fig.3, and p. 5). At this locality (481360), grey siltstones exactly similar to those at Burrow Head have yielded well preserved graptolites. The following have been identified by Dr. Strachan:

Cyrtograptus cf. centrifugus

Monograptus priodon

M. vomerinus var. basilicus

Retiolites geinitzianus

The outcrop is undoubtedly a tectonic wedge, and is bounded on each side by important strike faults.

2. Hawick Rocks.

The red siltstones of the Hawick Rocks frequently bear irregular elongate impressions suggestive of algal stipes. However, no structures definitely diagnostic of plant origin have been observed.

At one locality (468348), a red siltstone on the cliffs near Morrach Farm (467350) yielded a well-preserved mass of the colonial coral Heliolites cf. megastoma, Milne Edwards and Jules Haime. It measures approximately 7 x 7 x 10 cms. and lies in the bed in the correct orientation for growth, showing no evidence of erosion. Since the coarsest fragments of greywackes in the area do not exceed 3 mms., the emplacement by sedimentation of such a mass in a fine homogeneous siltstone seems most unlikely. Iceberg transport can be discounted, since corals live in tropical waters, and vegetation flotation is highly improbable considering the types of plants existing in Silurian times. Thus, although a fine silt is an unusual environment for a coral, it seems most probable that the colony was found in its original growth position. Since most modern colonial corals cannot tolerate depths of more than 180 feet below sea level (Moore, 1958), shallow-water deposition seems to be indicated for the Hawick Rocks. The plant-like markings of the red siltstones suggest confirmation of this environment, since preservation of marine algae would be unlikely in deep-sea sediments.

The commonest lutites of both the Hawick Rocks and the Riccarton Beds are grey-green siltstones and mudstones. These appear to be unfossiliferous, except for the very occasional presence of the trace fossils Palaeodictyon, Protovirgularia, and worm tracks (Plates 1, A & B).

The most important Hawick fossils from the stratigraphical aspect have been found on the west coast between Monreith and Cairndoon, in thin bands of dark grey shale, of which nine have been located (Fig.3). None of the bands exceed one inch in thickness, and they can only be detected where exposure is very good. The east coast around Innerwell Fishery (478493) has also been investigated, but the almost universal secondary iron staining makes it difficult to recognise subtle colour changes in the fine-grained beds; nevertheless, one suspected fossil band has been detected.

The most accessible horizon is situated at the western end of the beach below Kirkmaiden Church (365400), and immediately to the east of the headland Craigengour. This band is 1" thick, and has yielded reasonably good fossils, but has unfortunately been subjected to microfolding (F4, see pp.27-9), as have all the other bands in this region.

Dr. Strachan has examined these fossils, and considers that they are slender monograptids of the vomerinus type, which have been given the generic name Monoclimacis (Bouček). The absence of priodon types is noteworthy, and the fauna gives a general impression of the vomerinid types which occur at the top of the Valentian, in the zones griestonensis and crenulatus, a few of which range into the murchisoni zone. Dr. Strachan therefore considers that this fauna is older than that obtained from the Wenlock rocks of Burrow Head.

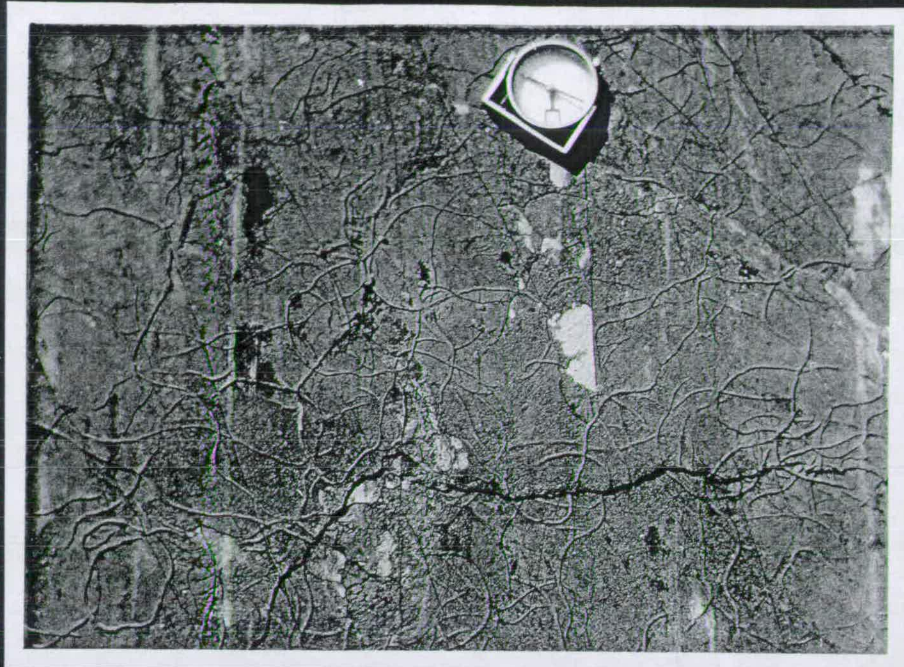
PLATE 1.

Trace fossils.

A. Worm tracks.

B. Protovirgularia.

A



B

X 3·5

PLATE 2.

F_1 folds.

A. Tight folds near Port Allen.

B. Maximum overturning of F_1 folds, as seen at Cruggleton Point.

A

B

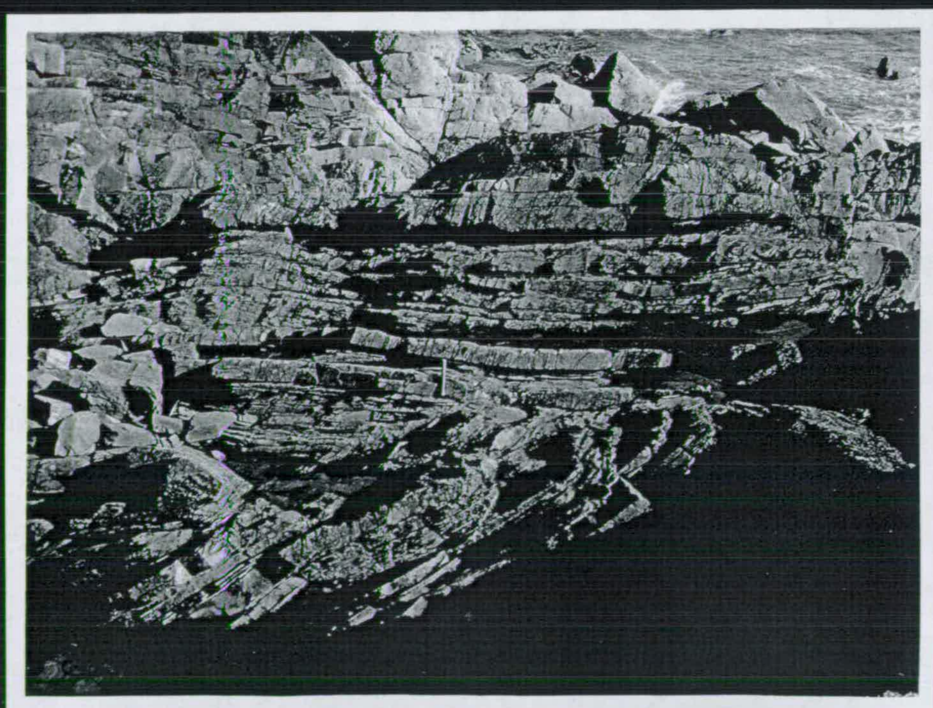


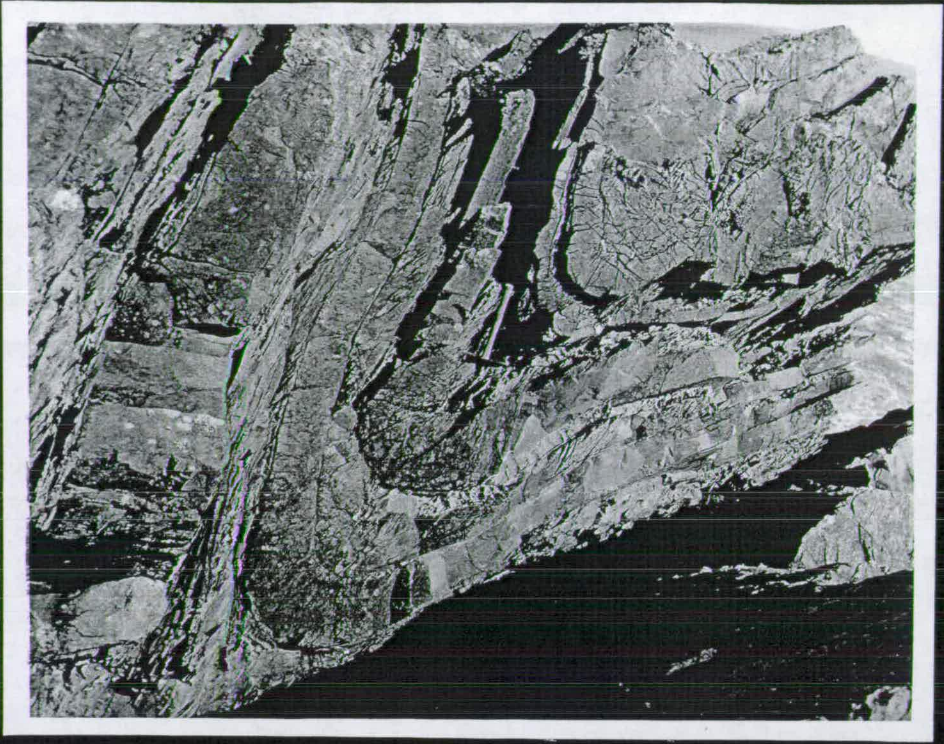
PLATE 3.

F_1 folds.

A. Syncline with strong axial plane cleavage, near Port Allen.

B. Isoclinal F_1 folds in massive greywackes (North Slate Craig, 487375).

A



B

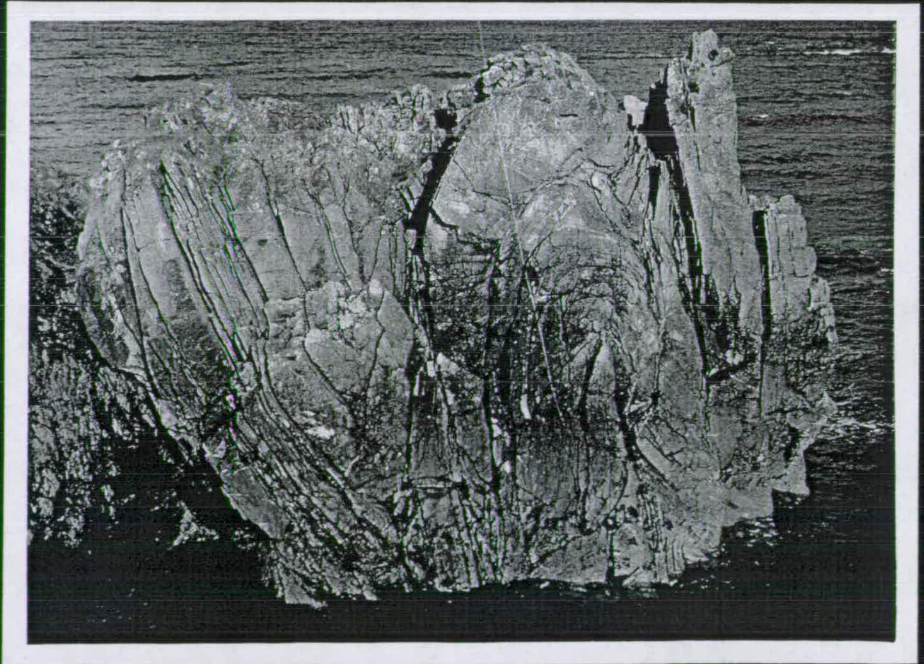


PLATE 4.

F_2 monocline near Jultock Point.

A. General view.

B. Cleavage in flat-lying central part of monocline.

A

B

PLATE 5.

F_2 folds.

A. Open anticline and syncline near Port of Counan.

B. Flat-lying central part of F_2 monocline with tight F_1 double fold in centre of photograph, overturned by F_2 refolding (Craigengour).

A

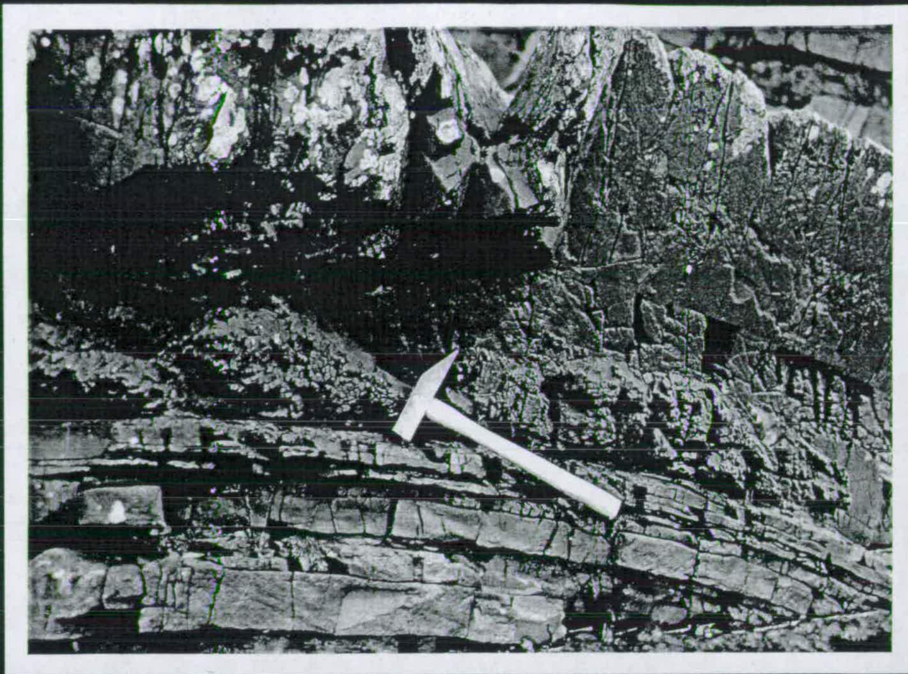
B

PLATE 6.

A. "Pencil" structure, due to intersection of F_1 and F_2 cleavages.

B. F_1 syncline with transverse F_3 cleavage (Carrickaboys).

A



B

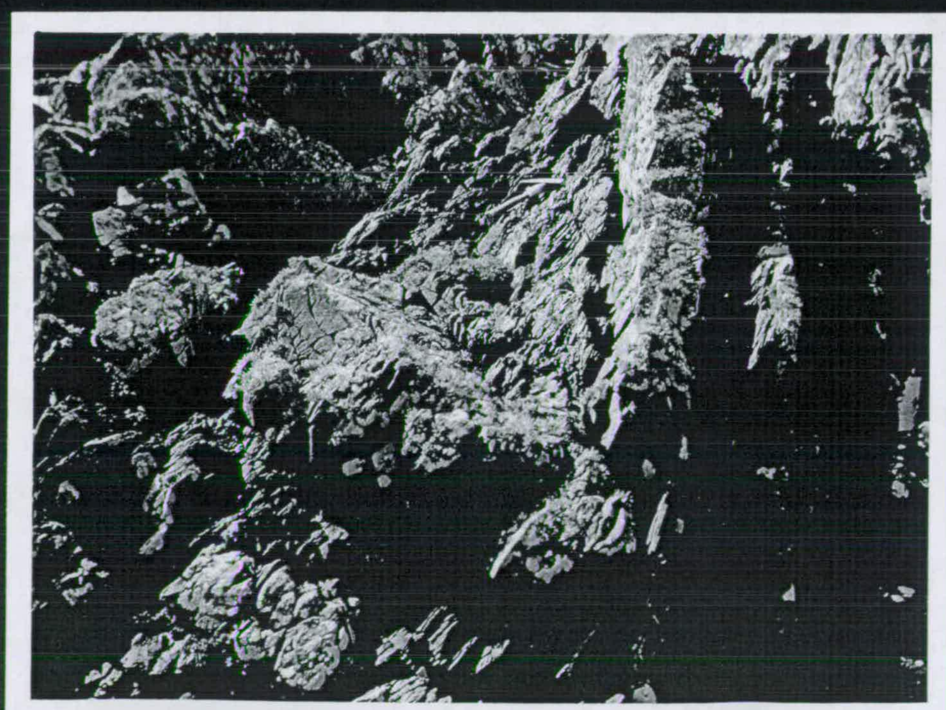


PLATE 7.

F_1 isocline refolded by F_3 axis (Cairn Head).

A. General view.

B. Close-up of F_1 closure.

A

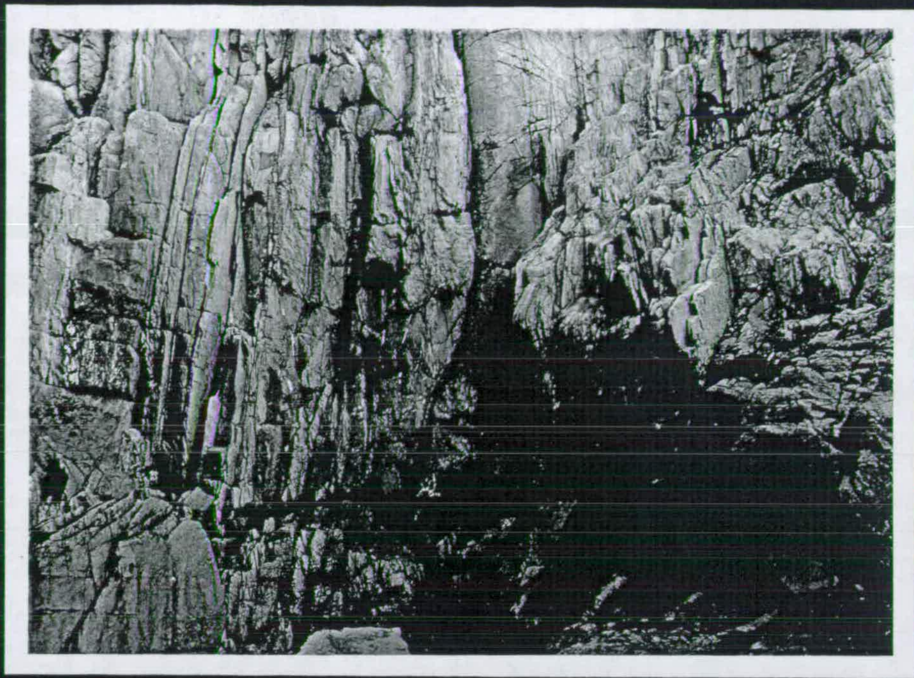
B

PLATE 8.

A. F_3 axis near Physgill.

B. F_3 axis intersected by F_4 axes (Shaddock Hole).

A



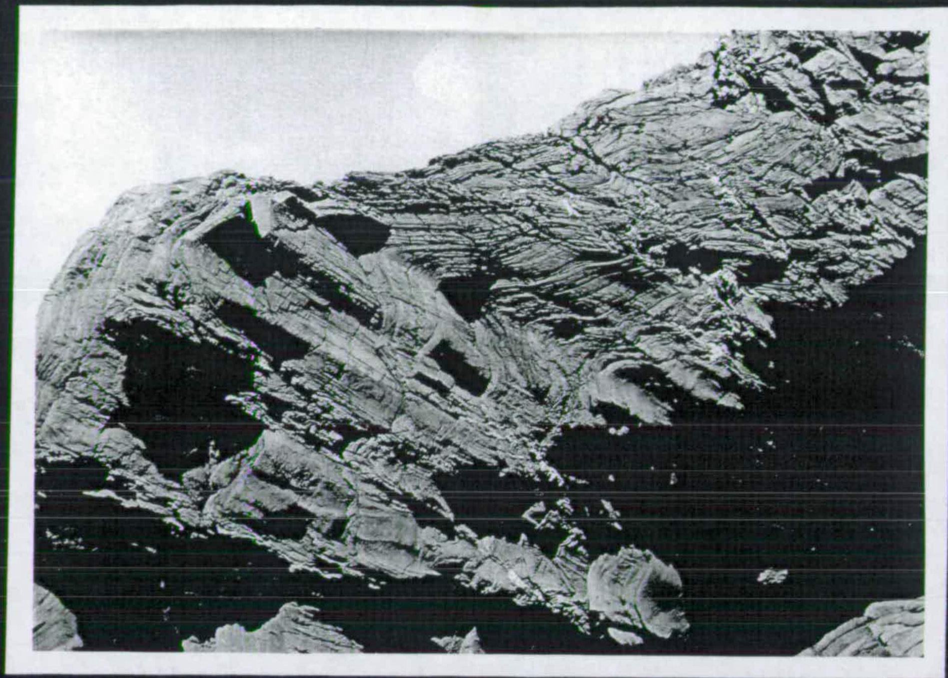
B

PLATE 9.

A. F_4 folds (Craigengour).

B. F_1 anticline and syncline refolded by F_4 fold with shallow axial plane (The Lag).

A



B

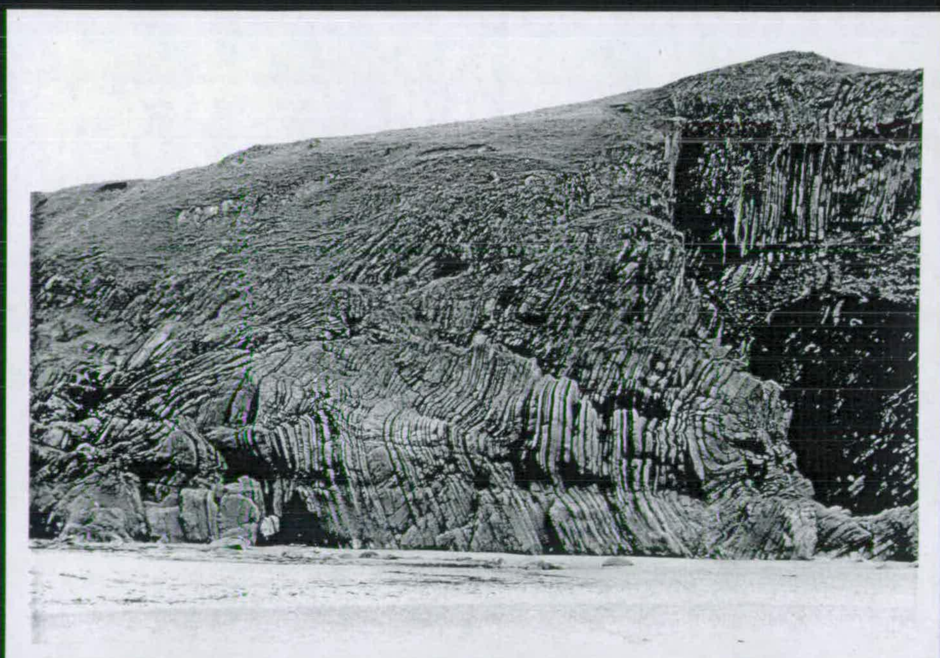
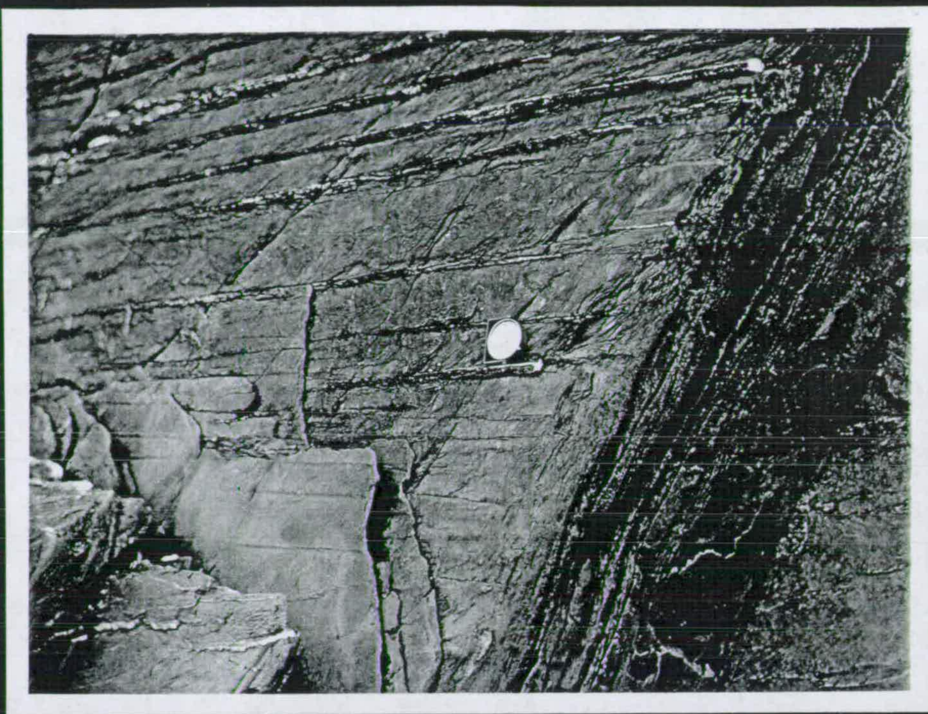


PLATE 10.

A. F_4 cleavage, filled with quartz/calcite veins.

B. Irregular quartz - mineralised thrust plane associated with F_4 folding and veining.

A



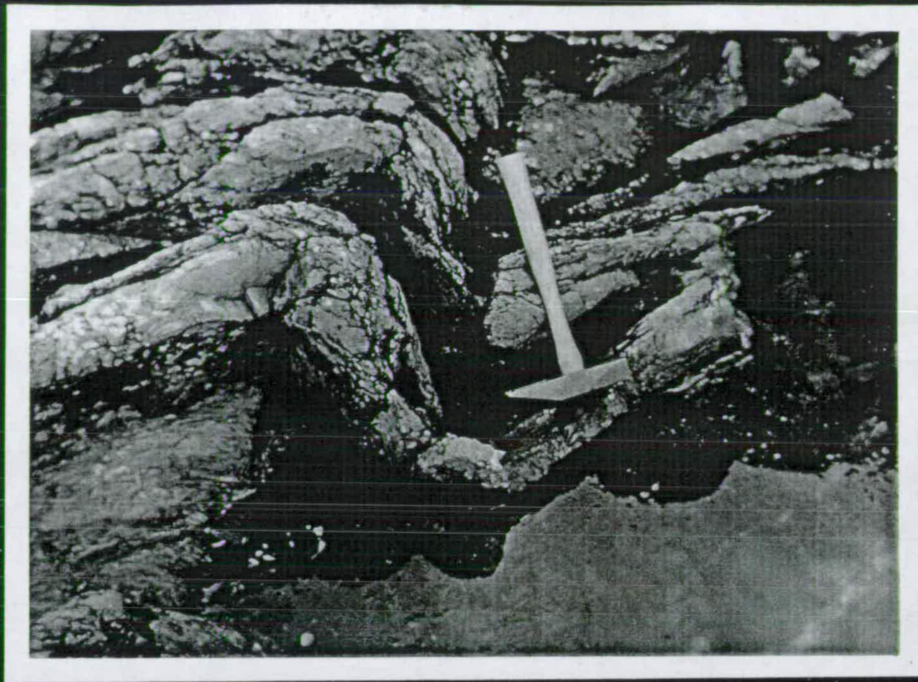
B

PLATE 11.

A. F_5 dextral kink band.

B. F_5 dextral kink band affecting a small hornblende lamprophyre dyke (Physgill).

A



B

STRUCTURE

1. Introduction.

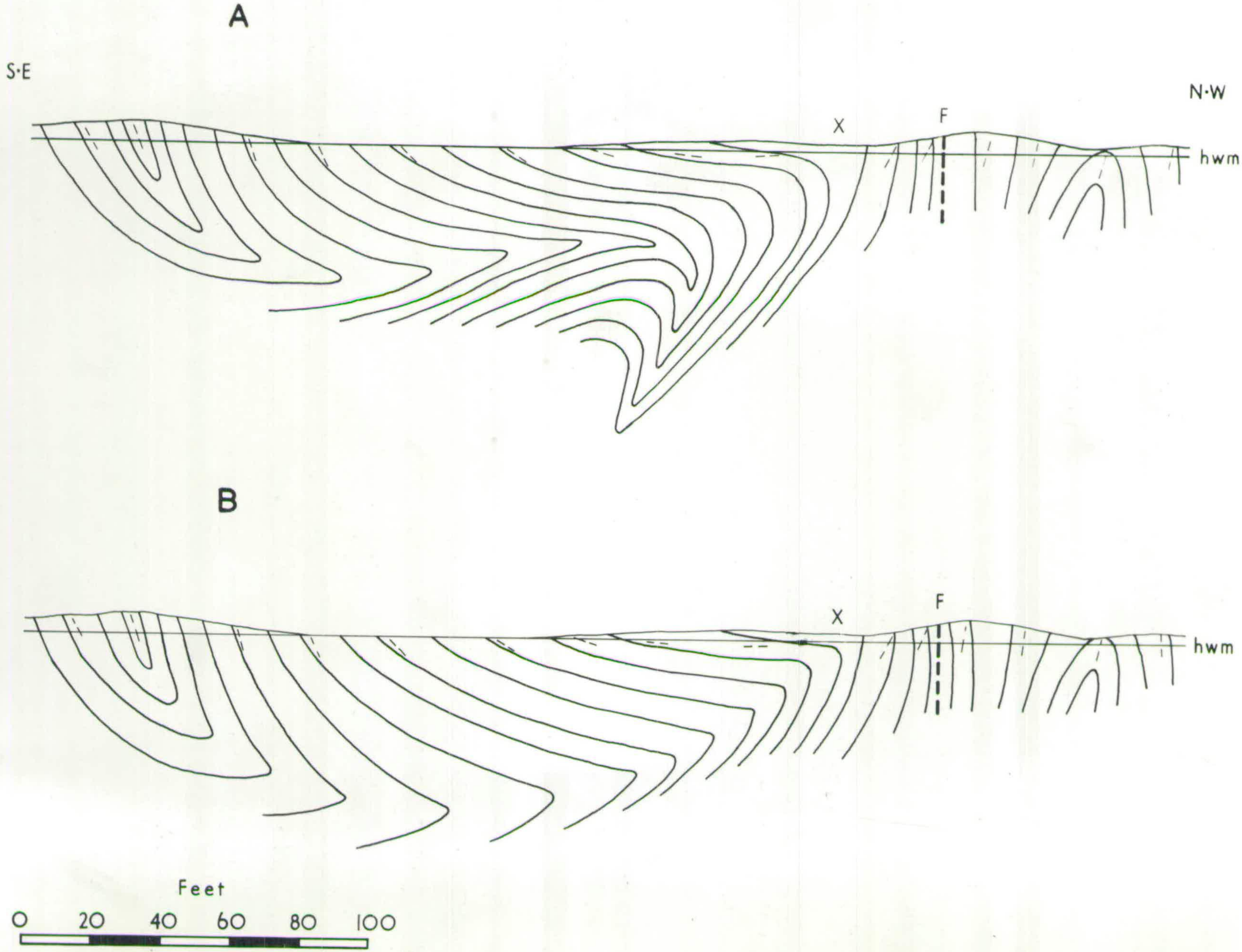
The structural history will be discussed firstly in terms of fold phases, after which fault and minor intrusive phases will be described, and an attempt made to interpolate them into the fold sequence. Joint data were also collected from a number of localities, but did not lead to any conclusive results.. Finally, the conclusions reached will be compared with results recently obtained from other parts of Southern Scotland and Northern Ireland.

2. Folding.

1. The Main fold phase.

The dominant trend of folds in the area is N.E.-S.W. Folds with this general trend vary in style from isoclines with strong axial plane cleavage to open folds (frequently monoclines) with a rather poor, "blocky" cleavage. In a few critical exposures it can be seen that the folds of open style have folded a pre-existing cleavage which can be related to isoclinal folds in the vicinity. For instance, an open northward-facing monocline 420 yards north of Jultock Point (488491) has folded an earlier cleavage, which maintains a constant spatial relationship to the bedding throughout the monocline. The early cleavage is folded

FIG. 4



Cross-sections of a refolded F_1 isocline near Jultock Point:
two alternative interpretations.

FIG. 4

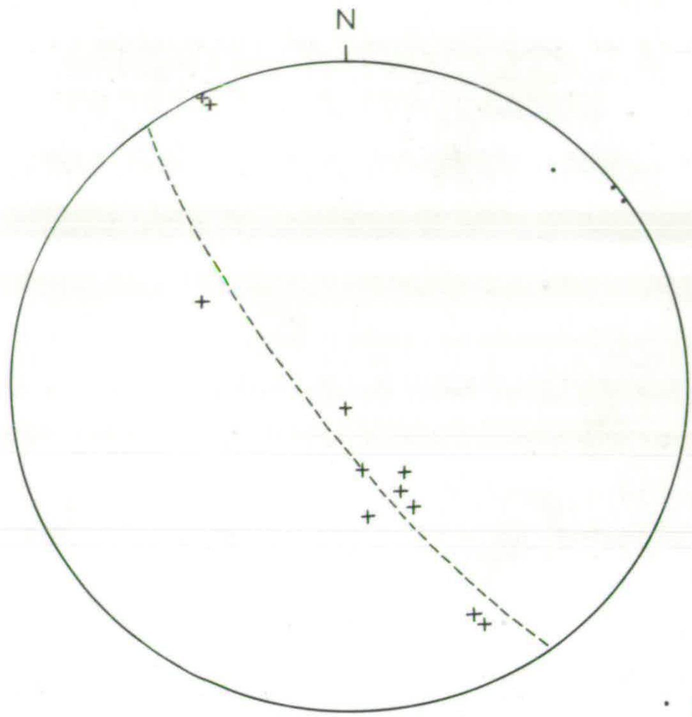
parallel to the axial plane of an isocline 30 yards to the south, which has also been refolded by the monocline. Since the exposed part of the monocline has refolded the inverted limb of the isocline, the flat-lying beds of the central part of the former are inverted. In Fig.4 two reconstructed sections across this structure are shown, which differ at ground level only in the cleavage relationships seen at the point X. Here, unfortunately, the cleavage is indefinite, and one cannot be sure whether refolding has taken place as illustrated in 4A or 4B, but the former alternative is considered to be more likely, (Plate 4).

Another monocline, situated 250 yards to the north, is similar to the above in all respects except that the flat-lying central part faces upwards. These two exposures demonstrate the effects of two episodes within the Main fold phase, which will be denoted F_1 and F_2. Other instances of open (F_2) folds which have refolded isoclinal or near-isoclinal (F_1) folds with the same N.E.-S.W. trend may be found elsewhere. At Jultock Point an F_2 anticline folds F_1 cleavage, which maintains the same angular relationship to the bedding throughout the fold. At Craigengour (364402) two sharp F_1 folds lie with axial planes horizontal due to rotation by a large open F_2 monocline, (Plate 5B). Both F_1 and F_2 cleavages have been destroyed by strong quartz veining parallel to the axial planes of later folds (F_4, see p. 28).

In the examples described above, F_2 cleavage parallel to the axial planes of the open folds is poor or non-existent.

FIG. 8

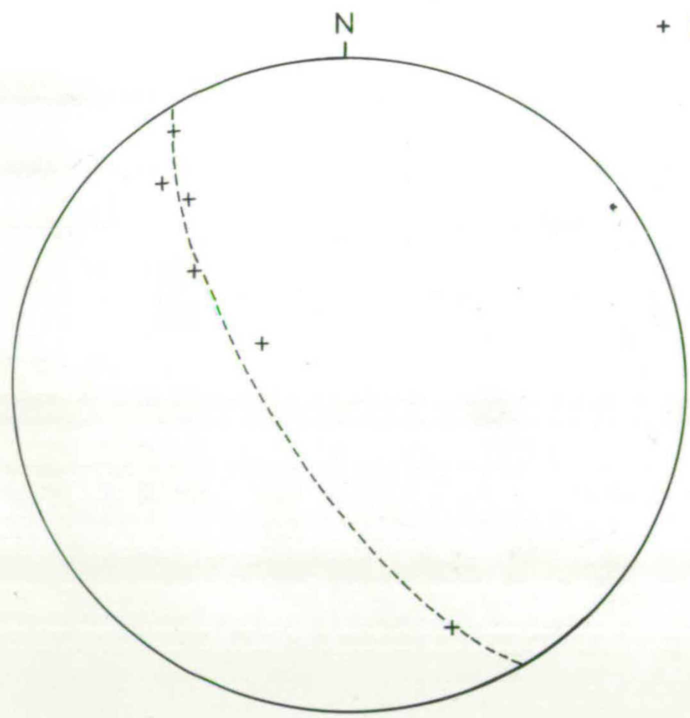
A. Monoclines near Jultock Point



i.e. F_1 axis $\equiv$ F_2 axis

· F_2 axes

+ Poles to F_1 cleavage



B. Anticline near Eggerness Point

Examples of F_1 cleavage folded by F_2 axes.

Frequently, however, the intersection of an approximately planar F_2 cleavage with a refolded F_1 cleavage produces an irregular "pencil" structure, (Plate 6A). In some F_2 folds the earlier cleavage has been entirely destroyed, and in many cases F_1 and F_2 axes can only be distinguished on the basis of style. There are also numerous examples of folds intermediate between isoclines and open folds which cannot be definitely assigned to either F_1 or F_2, and are therefore referred to under the general term 'Main phase folds'.

a) F_1.

Early isoclinal or near-isoclinal folds are much commoner than undoubted later open folds, (Plates 2&3) but the absolute relative importance of F_1 and F_2 cannot be assessed on account of the numerous folds of intermediate type. In the discussion which follows, these intermediate folds are included with the isoclines.

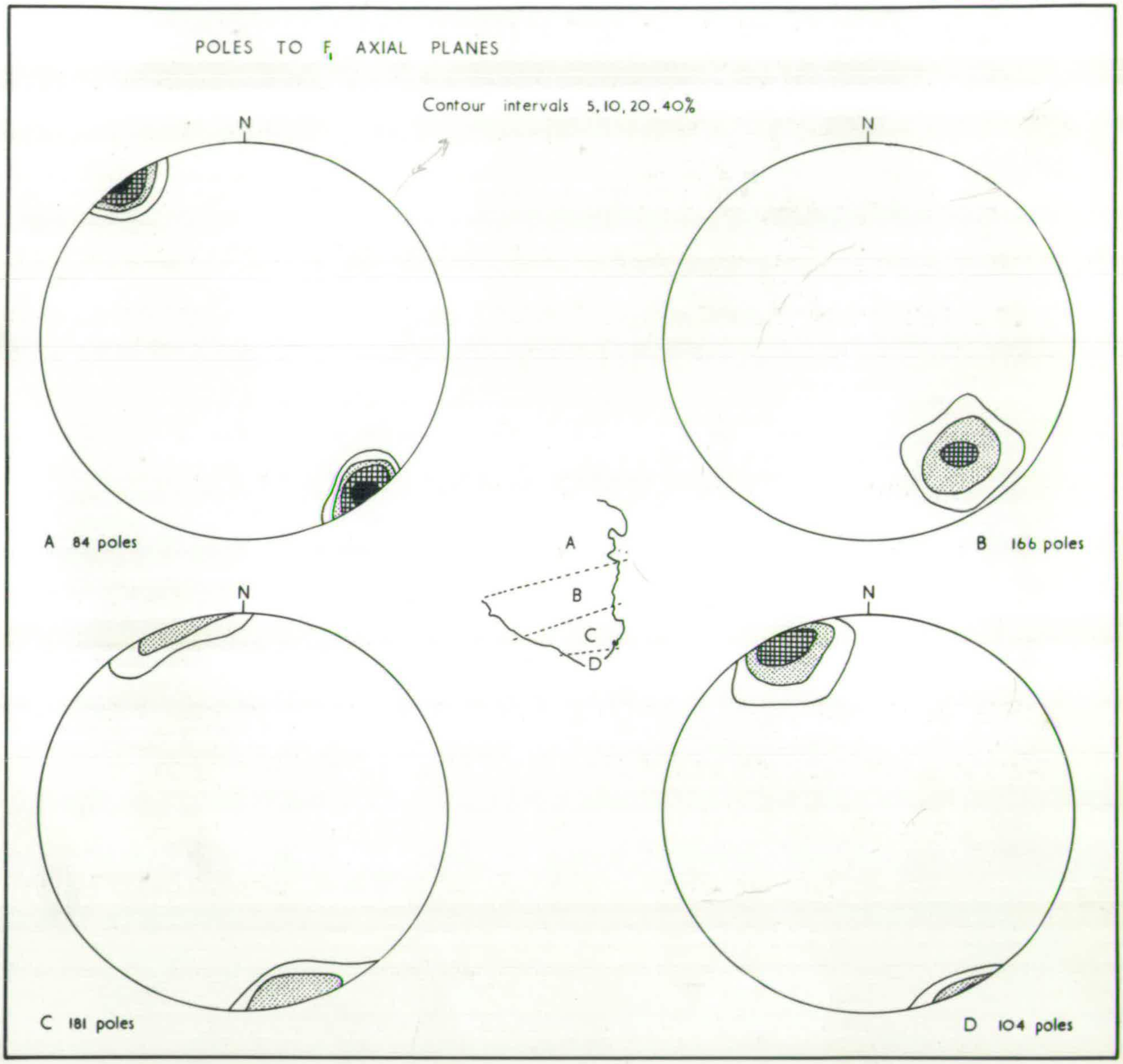
The orientation of axes and axial planes has been measured throughout the area, which has been divided into four subareas to emphasise the geographical variations.

(i) Axial planes.

North of Sliddery Point (486441) the modal orientation is vertical 050 (Fig.5, A), while between Sliddery Point and Shaddock Hole* (477397) the dip of the axial planes decreases to

* This name is applied to a cove 100 yards north of the feature marked as the Howe Hole of Shaddock on the 6" and 25" maps.

FIG. 5



POLES TO F_1 AXIAL PLANES
Contour intervals 5, 10, 20, 40%
N
A 84 poles
B 166 poles
C 181 poles
D 104 poles
A
B
C
D

a mode of 60°N, with the same azimuth (Fig.5,B). From Shaddock Hole to a point south of Isle of Whithorn harbour (Fig.5,C) there is marked variation in the azimuths of the axial planes about a mode of 85°N 075. In the fourth sub-area (Fig.5,D) dip and azimuth are fairly consistent about modal values of 80°S 055.

(ii) Axes.

To illustrate the variation in axes the number of sub-areas may be reduced to two. North of Shaddock Hole (Fig.6,A) axes plunge consistently to the north-east (modal value 20° 045), whereas south of Shaddock Hole there is a considerable development of south-westerly plunge, although the mode lies at 20° 070 (Fig.6,B).

(iii) Significance of variations.

The axial plane variation has two components: a change in dip throughout the area, and a variation of azimuth which is practically restricted to one sub-area (Fig.5,C). The latter variation is almost certainly due to refolding by F_3, since it occurs in the sub-area in which F_3 folds are most abundant, and since azimuth variation is likely to have resulted from refolding about vertical axes. The variation in dip of F_1 axial planes may be an original feature of F_1 folding, perhaps due to some modifying influence such as variable depth of basement. However, it could equally well be the result of refolding by the

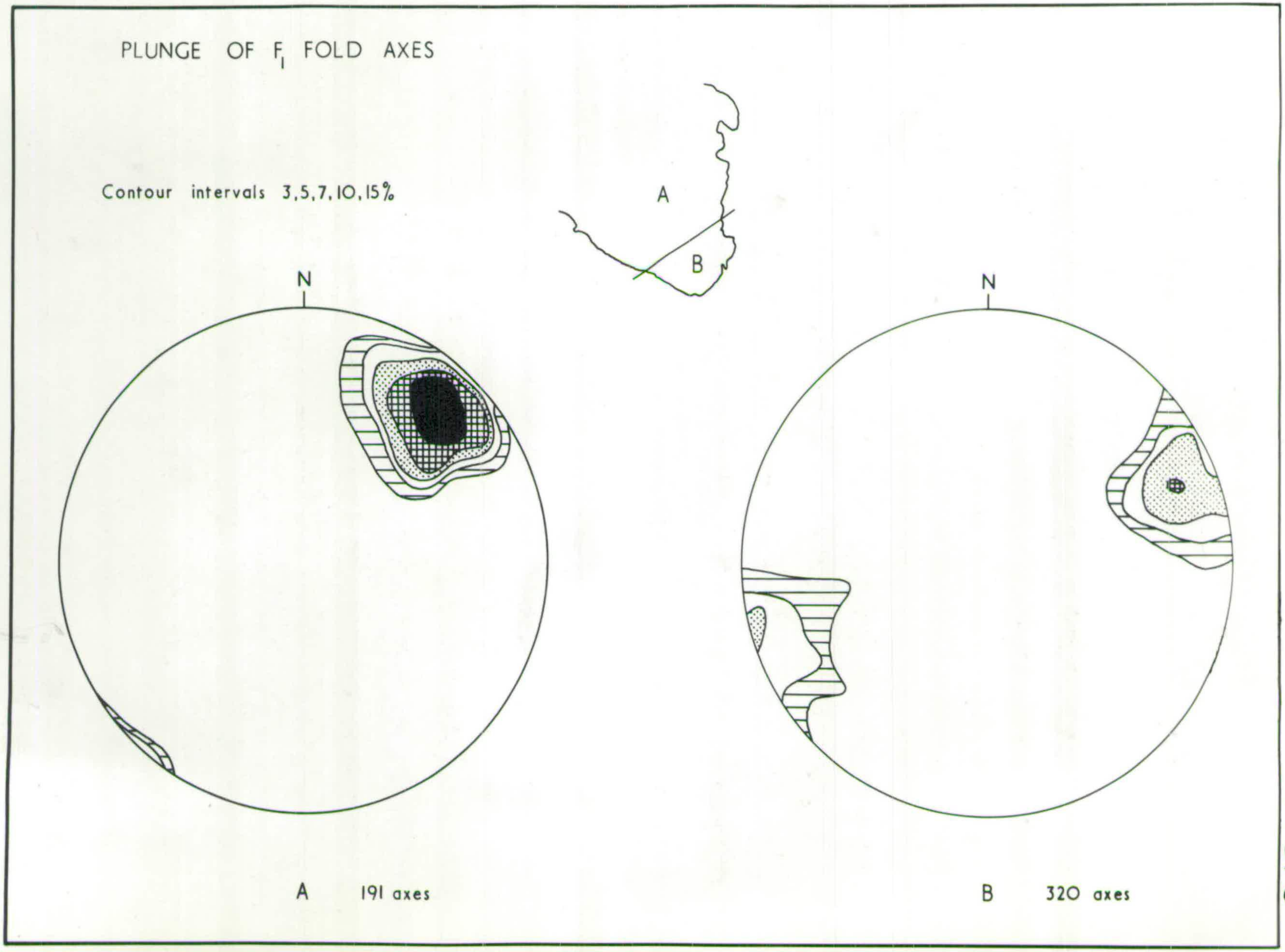

PLUNGE OF F_1 FOLD AXES
Contour intervals 3,5,7,10,15%
A
B
N
N
A 191 axes
B 320 axes

FIG. 6

F_2 monocline which forms the major structural element of the Whithorn area (pp.22-3, and Fig.30).

The variations of axial plunge could also be explained as original F_1 features, but it is more likely that later refolding is responsible. Thus the variation from north-easterly to south-westerly plunge in sub-area B (Fig.6) is probably due to tightening of F_1 axes by F_2 refolding. It is noticeable that the most variable F_1 axes are isoclines, which are thought to have become isoclinal through the tightening effect of F_2. However, there is an additional azimuthal spread of axes, especially in sub-area B as compared with sub-area A (Fig.6), and this is thought to be due to F_3 refolding. The fact that the change in F_1 axial azimuth occurs at Shaddock H ole, which is the northern limit of F_3 axes, is probably significant in this context.

b) F_2.

The later folds of open style are less common than F_1 folds, and are more difficult to measure accurately. They are therefore less suited to stereographic analysis and no definite pattern of orientation according to sub-areas is apparent (Fig.7). As already described (p. 18) F_2 folds in some cases refold inverted limbs of F_1 folds, and therefore produce downward-facing structures such as the antiform* and synform at Thief's

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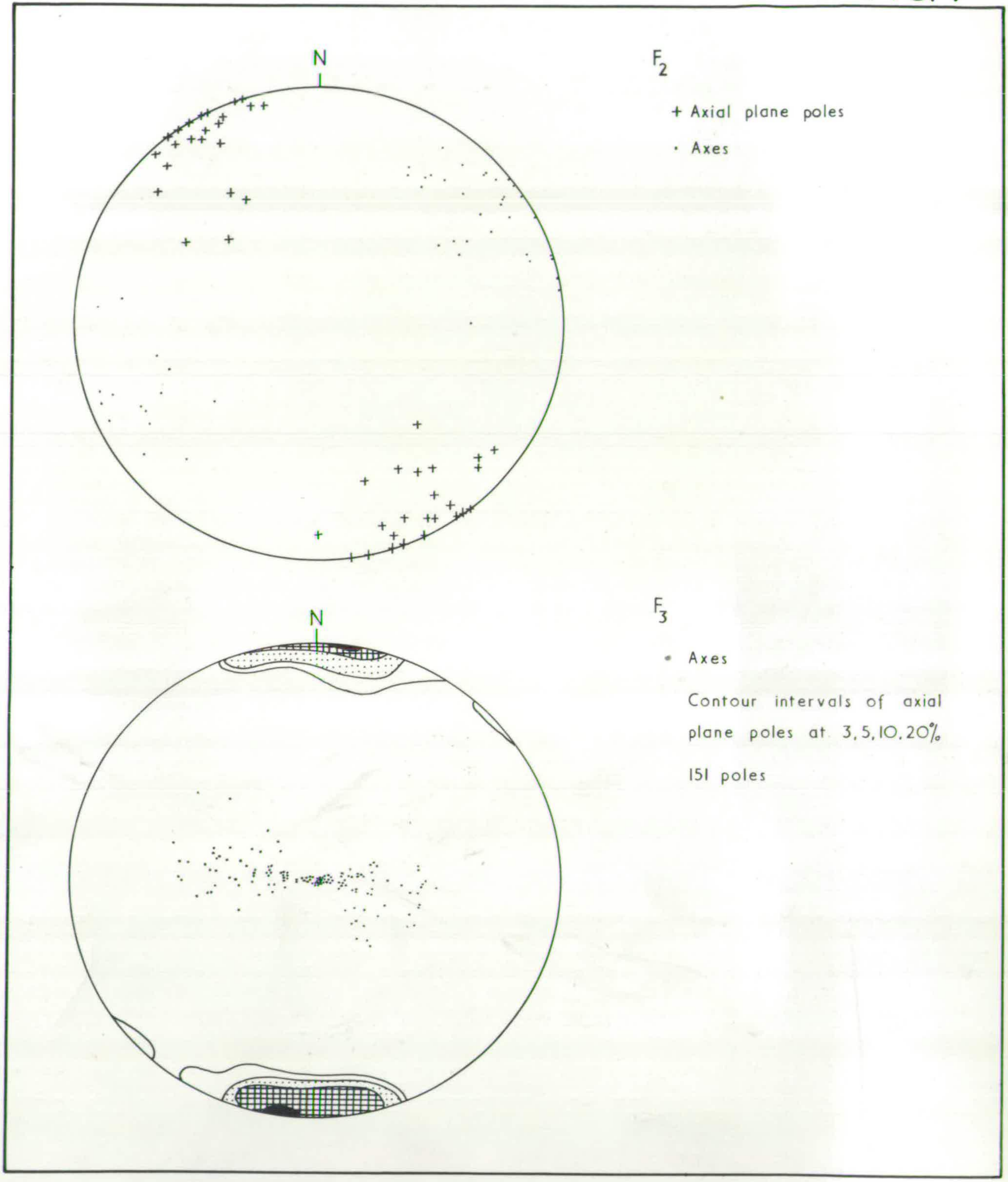
* In this thesis the term antiform is used to denote a fold with anticlinal form, but with younger beds in the core. The term synform is used with the opposite sense. (cf. Bailey and McCallien 1937).

FIG. 7



F_2 and F_3 : Plunge of axes and poles to axial planes.

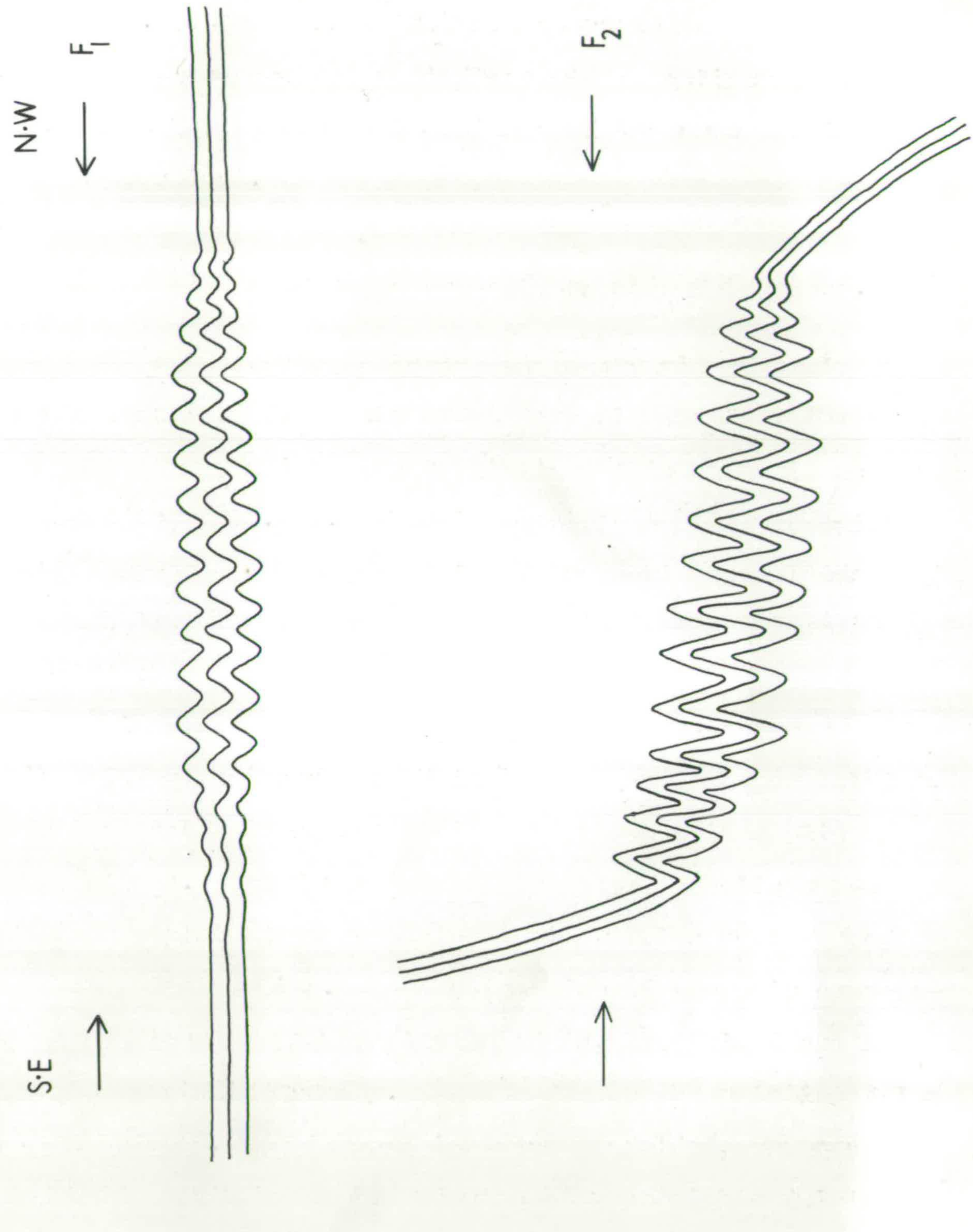
Hole (464344). Both these folds have approximately horizontal axes, and are therefore quite different to F_3 antiforms and synforms which are formed by the plunge of the axes passing through the vertical.

c) Major structures of the Main fold phase.

The folds observed in the field are all of small or intermediate scale. Synthesis of structural data from the whole area shows that the major structural element is a gentle northward-facing monocline (Fig.30). This is consistent with the major structures proposed for other parts of the Southern Uplands (Craig and Walton 1959, Kelling 1961, Walton 1961, Gordon 1962, Anderson 1962).

Using the principle that minor structures frequently resemble major structures formed in the same episode of folding, it seems reasonable to correlate the major monoclines with F_2 minor monoclines. The formation of the major monoclines can therefore be explained by supposing that F_1 folds were formed only within certain belts. On continuation of the main compressional phase along the same principal axis, the folded and unfolded belts would react differently. In the former the existing folds would be tightened, and in some instances refolded, whereas the unfolded belts would be steepened without appreciable folding (Fig. 9).

FIG. 9



Suggested mode of formation of major monoclinal structures.

This seems to be the most feasible way of producing the major monoclines, but poses the problem of the selective location of F_1 fold belts. The latter may have been controlled by irregularities in the underlying basement, which could hardly be detectable, even by geophysical means. Whatever the explanation, the concentration of F_1 folds into certain belts remains an observable fact, which has also been noticed in parts of the Scottish Highlands (Howkins, 1961, p.119). In the Highlands, however, it is possible that the local absence of F_1 folds may be due to obliteration by later fold movements.

2. F_3.

The third phase of folding differed considerably from the two preceding phases, because the rocks had become steeply inclined throughout the area. The response to a horizontal maximum stress was therefore the p roduction of folds with steeply plunging axes and vertical axial planes, and involved a nearly horizontal a direction. The modal trend of these axes is about 095 (Fig. 7), and they tend to be concentrated into zones which are comparable to those found in Kirkcudbrightshire (Craig and Walton 1959). The main zones of the Whithorn area are found on the east coast at Carrickaboys (488378), Cairn Head (487383) and Shaddock Hole (477397) (Fig. 10). They appear to be elongated parallel to the regional strike, and reappear on the west coast in

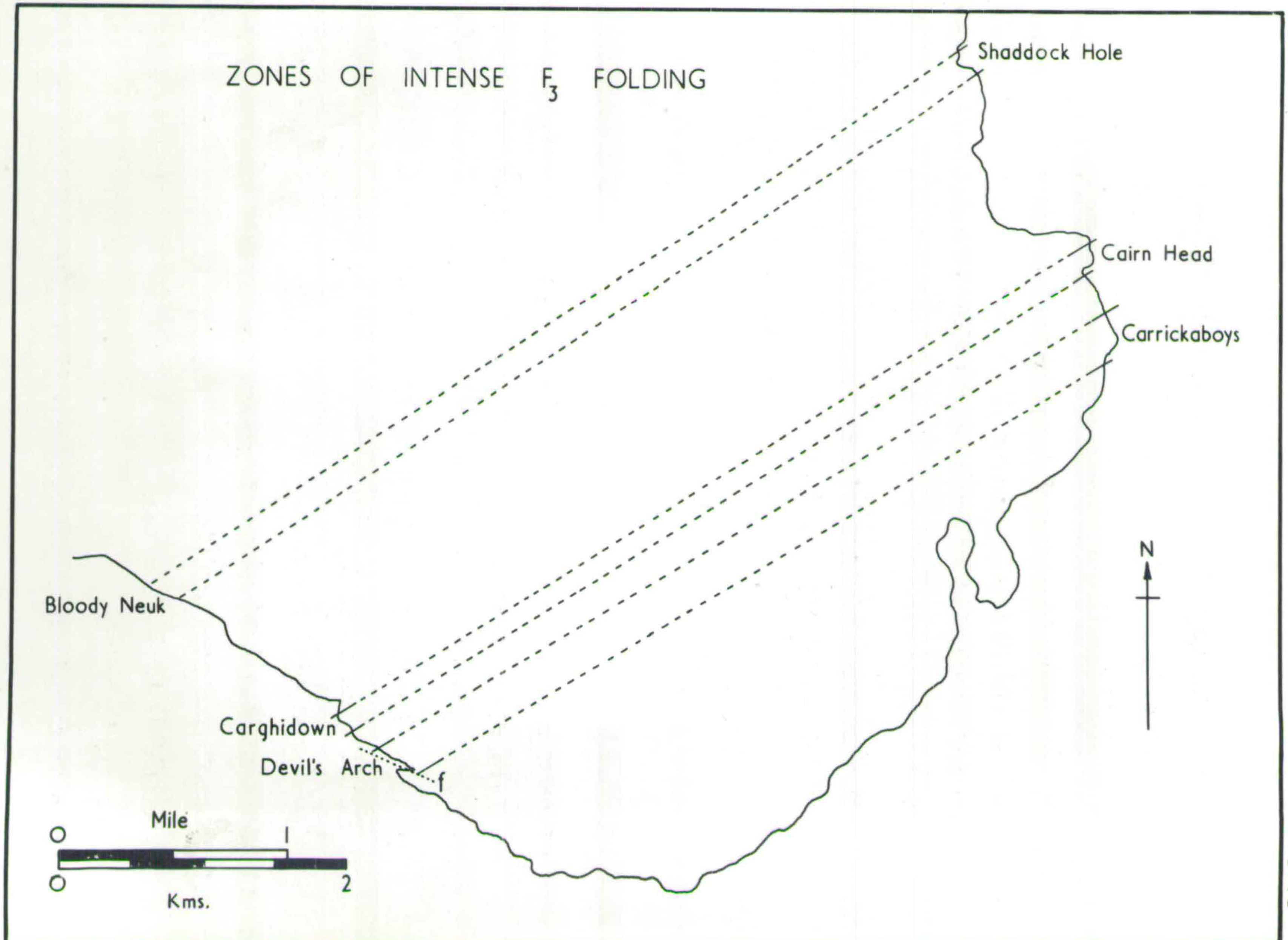

ZONES OF INTENSE F_3 FOLDING
Shaddock Hole
Cairn Head
Carrickaboys
Bloody Neuk
Carghidown
Devil's Arch
f
N
Mile
0
1
0
2
Kms.

FIG. 10

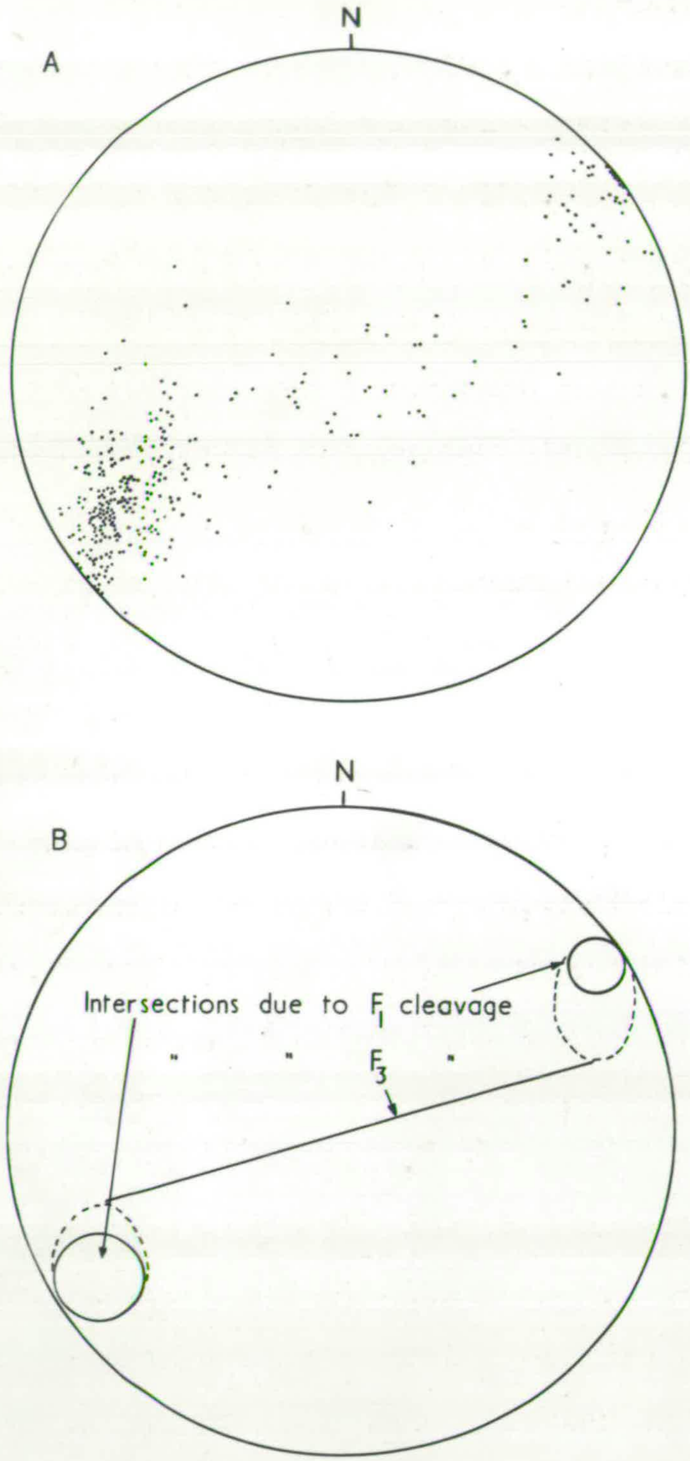
the appropriate places (with the possible exception of the Shaddock Hole zone). They are frequently accompanied by complex shearing, both within the zones and at their margins. It is possible that their location has been determined by pre-existing fault or shear zones formed parallel to the regional strike.

In the southern part of the area (ie. south-east of a line between Port of Counan (418362) and Port Allen (478411)), many F_3 folds occur outside these restricted zones. F_3 axes also occur at Monreith(358407), while cleavage which is thought to be associated with F_3 is found throughout the area, even where F_3 axes are absent. This cleavage may be recognised as younger than F_1 folds because it cuts across them at an oblique angle without being folded (Plate 6B). The cleavage is always situated in a clockwise direction relative to the fold axial planes, with which it makes an angle varying from 10-25°. However, it is not always possible to distinguish F_3 from F_1 cleavage, especially on the limbs of the folds, and they have not been separately identified on the map, Fig.1. However, since most of the cleavages measured were those markedly transverse to the bedding, it is thought that the majority are of the F_3 generation.

Stereograms of cleavage/bedding intersections constructed from adjacent cleavage and bedding measurements give what is at first sight a somewhat disconcerting pattern (Fig. 12). From concentrations of points near the perimeter on either side, a vertical great circle crosses the stereogram, but the great

FIG. 12

Cleavage bedding intersections, Innerwell to Eggerness



circle and the horizontal maxima are disorientated relative to each other, and the combined effect is to give an S-shaped distribution. This distribution results from the intersection of two sets of cleavage with folds whose axial planes are parallel to one of the cleavages, but are transverse to the other. Thus the horizontal maxima are due to F_1 cleavage intersecting the bedding, while the vertical great circle is produced by F_3 cleavage cutting bedding planes orientated by folding along F_1 axes (Fig. 12). The intersections plotted were determined from cleavage and bedding measured between Innerwell and Eggerness Point. Of the two near-horizontal maxima, the south-westerly plunging one is stronger than that which plunges to the north-east. The reason for this is not known, since the general plunge of F_1 axes in this region is a gentle one towards the north-east (Fig. 5,A).

The map (Fig. 1) shows that the orientation of cleavage (mostly F_3) varies throughout the area. In the south, where F_3 axes are present, the cleavage tends to be parallel to the axial planes (ie. with a modal trend of about 095). When traced northward out of the region where F_3 axes occur the cleavage gradually assumes a different attitude, moving in an anti-clockwise direction. Between Eggerness Point (493464) and Innerwell Port (479493) it has a fairly constant trend, with a mode of about 065, which is always situated clockwise from the F_1 F_2 axial trend (mode about 050). This change in attitude of the cleavage may be considered as a fanning effect away from the zone of concentration of the folding, just as cleavage fans out, away from the axis of an anticlinorium.

The most instructive exposure of F_3 folds is at Cairn Head (487383). Here three isoclinal F_1 folds (two anticlines and a syncline) have been refolded about two steeply plunging F_3 axes with a strong axial plane cleavage (Fig. 11, Plates 7). F_1 cleavage can still be seen in the hinges of the isoclines, but has been destroyed elsewhere by F_3 refolding. This evidence clearly shows that F_3 is younger than F_1, which confirms the age relations deduced from F_3 cleavage intersecting F_1 folds (p. 24). A few examples have been found where F_3 cleavage cuts transversely across F_2 folds, eg. a large open monocline on a rock accessible at low tide off Stein Head (485370). A horizontal antiform and synform at Thief's Hole (464344) also show transverse F_3 cleavage.

From theoretical considerations it would seem unlikely that two coaxial fold phases as closely related with regard to stress conditions as F_1 and F_2 would be separated in time by a completely different set of movements such as F_3. In addition, the conditions necessary for the formation of steeply plunging axes (ie. steeply dipping beds) were not fully achieved until after the formation of the major monoclines, which, as suggested above, can be correlated with minor F_2 folds. These considerations, together with the evidence reviewed above suggest F_1, F_2, F_3 as the most plausible sequence, although separate recognition of the three phases does not imply discontinuity of

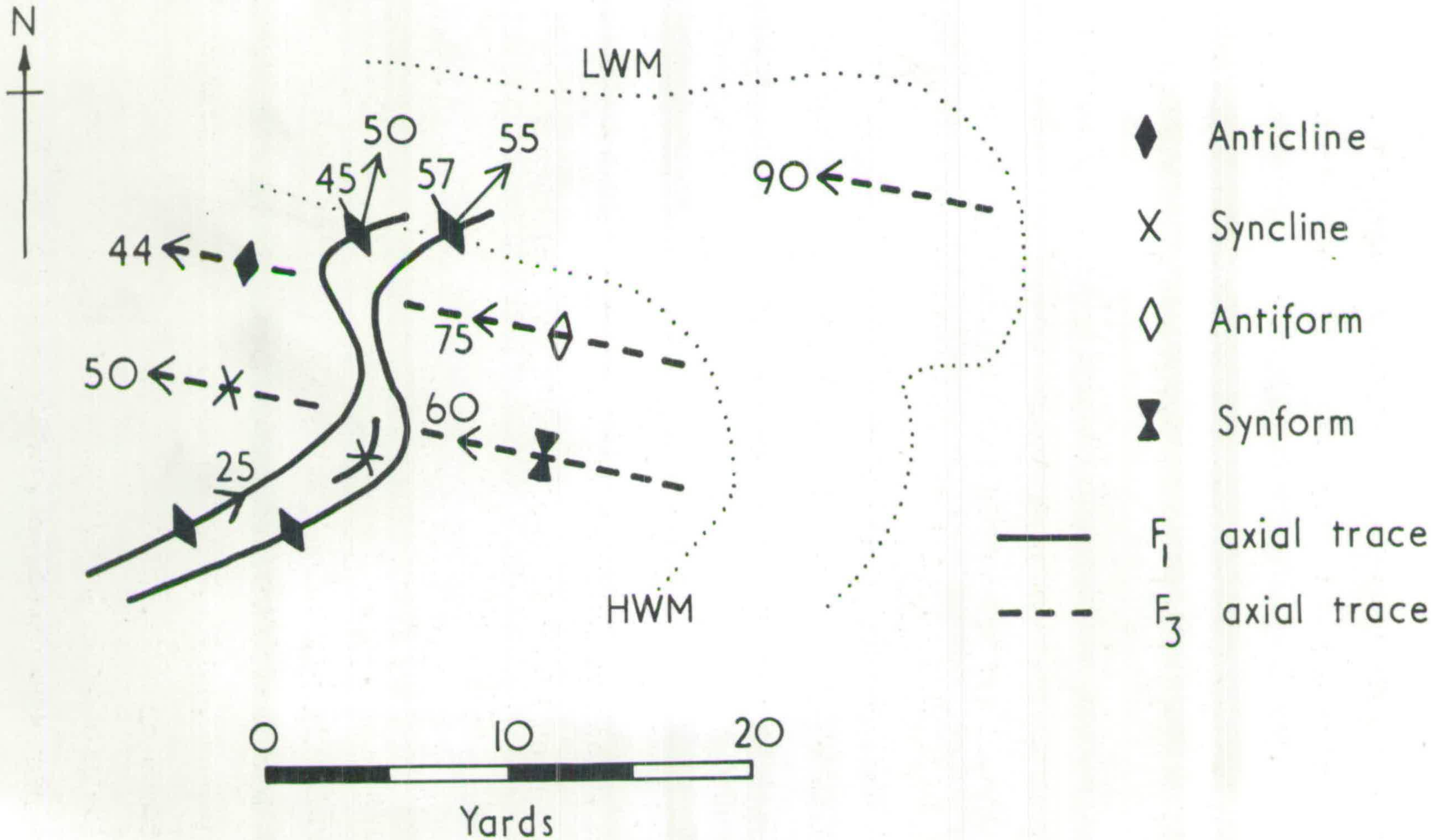


FIG. 11

Map of F_1 isoclines refolded by F_3 axes at Cairn Head.

deformation.

F_3 axes vary in direction and amount of plunge, but if the area is considered as a whole, variation is symmetrical about the vertical (Fig. 7). This suggests that the folds were produced with predominantly vertical axes, and the occasional extreme variations in plunge (also noted by Dearman, Shiells and Larwood (1962) on the Berwickshire coast) are probably due to later refolding of the vertical axes.

3. F_4 and F_5.

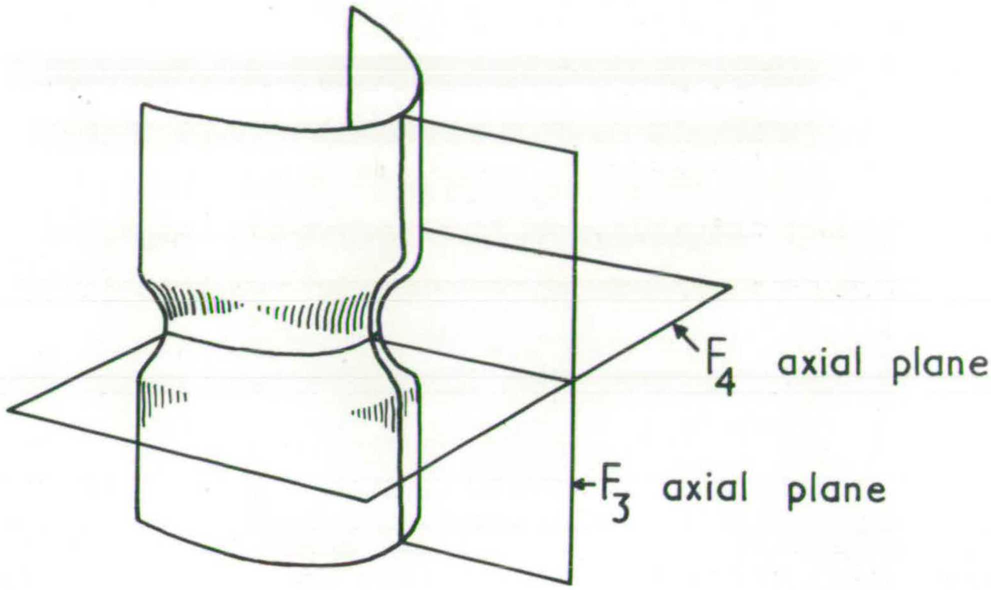
The two remaining fold phases are relatively unimportant as regards magnitude and extent. F_4 folds have approximately horizontal axes and axial planes, whereas F_5 axial planes are sub-vertical, with axes varying in plunge according to the orientation of the beds traversed. Folds of the two types intersect on the coast at Sliddery Point (486441), but since the axes and axial planes are mutually perpendicular, the age relationship cannot be demonstrated (Fig. 14). However, various other factors strongly suggest that F_4 is the older phase, and it will therefore be described first.

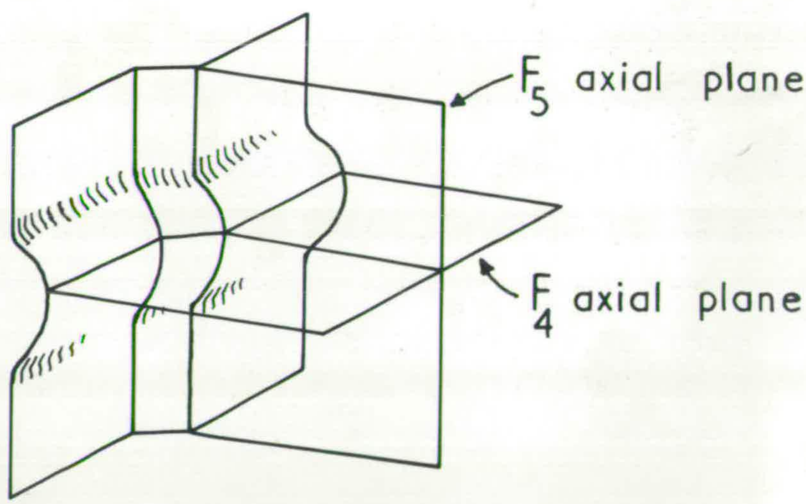
a) F_4.

Folds with near-horizontal axial planes are represented on the east coast between Garlieston and Innerwell by small

FIG. 14

Re-folding of F_3 by F_4





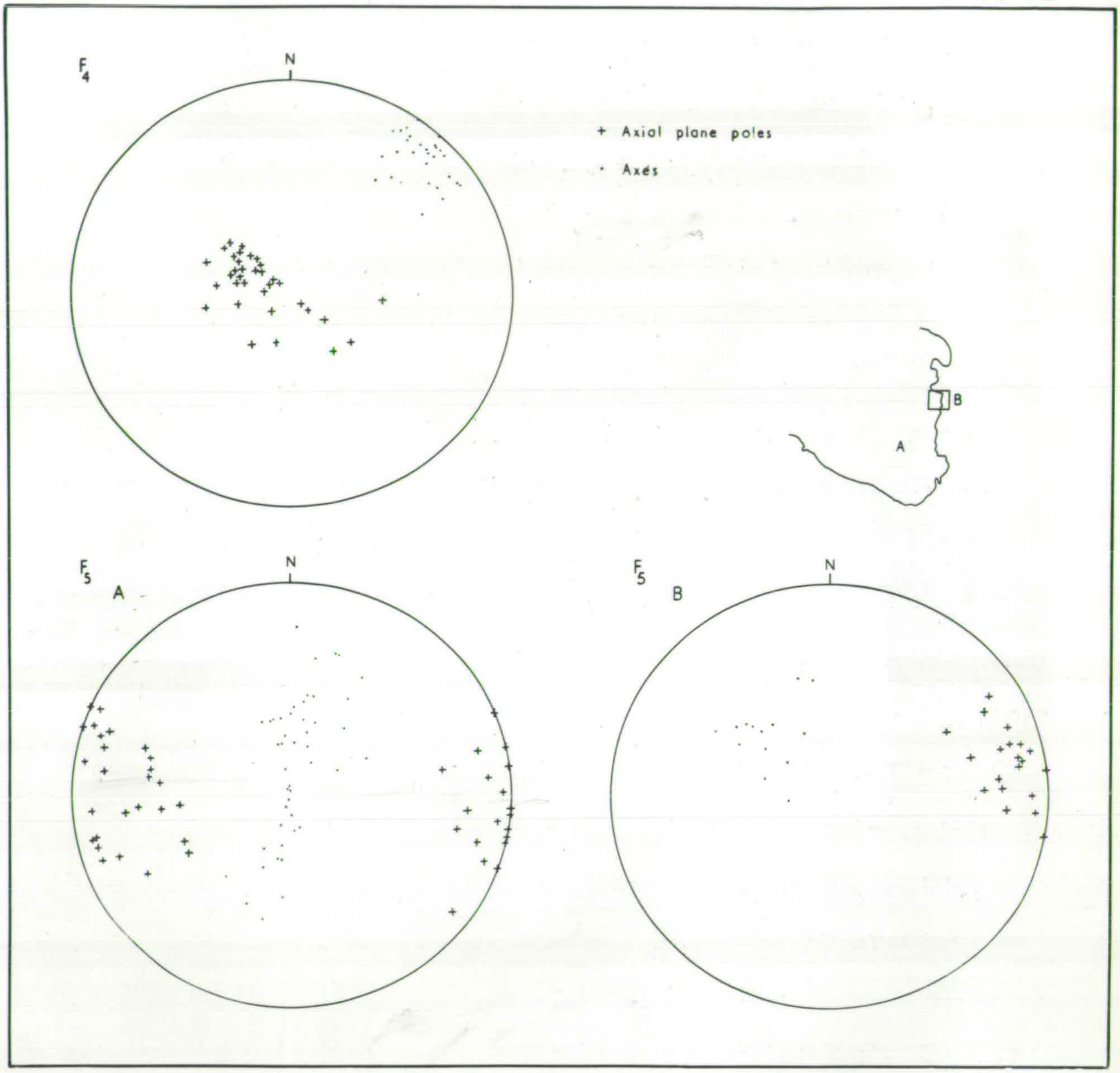
Intersection of F_4 & F_5 axes

crinkles of amplitude up to a few inches. South from Garlieston F_4 folds increase in amplitude to a maximum of about 2 feet, while on the west coast, between Cairndoon (375388) and Monreith, F_4 folds with greater amplitude may be seen, reaching their most impressive development between Benbuie and The Lag. Here F_4 folds of up to 20 feet amplitude with strong axial plane cleavage refold F_1 axes so as to distort their axial planes to a considerable extent (Plate 9B).

The orientation of F_4 axes and axial planes is fairly consistent throughout the whole area (Fig. 13). The axes plunge at low angles to the north-east, while the axial plane poles spread out along a great circle inclined steeply towards the north-east. The greater-amplitude F_4 folds between Cairndoon and Craigengour frequently show a development of quartz veins parallel to their axial planes. In some cases the veins are parallel to and associated with irregular quartz-mineralised thrusts which are considered to have been formed together with the F_4 folds, on account of their geographical association, and orientation parallel to the axial planes of the folds.

F_3 and F_4 folds may be seen in conjunction only in the neighbourhood of Shaddock Hole. Here, many F_3 axes occur, varying widely in plunge about the vertical, while individual axes change from westerly plunge, through the vertical, to an inverted easterly plunge (or vice versa) when traced along their axial planes. Two particular axes at Shaddock Hole are thought to indicate the way

FIG. 13



F_4 and F_5 : Plunge of axes and poles to axial planes.

in which F_3 has been refolded. These axes, which plunge vertically throughout most of their exposed lengths are interrupted periodically by folds with gently inclined axial planes (F_4). Where the two intersect, the F_3 axes change rapidly in direction and amount of plunge (Fig. 14, Plate 8B) simulating within a small area the variations in plunge of F_3 axes seen elsewhere at Shaddock H ole, and in other parts of the area. The difference between this interpretation and that given by Dearman et al (1962) will be discussed later (p. 67-69).

b) F_5.

By contrast, F_5 folds do not exceed one foot in amplitude, they lack axial plane cleavage, and everywhere exhibit a brittle style which has been described as "kink banding" (Voll, 1960). This term refers to folds which occur as isolated pairs formed by localised shear couples giving sharply angular folds, which are usually bounded by shear surfaces (Plate 11A). Compared with these, F_4 folds affect considerable masses of rock, and have the smoothly rounded hinges characteristic of plastic deformation (especially at Benbuie). Such a style is less likely to develop in the closing stages of a deformation history, and F_4 is therefore considered to be older than F_5. Other evidence of the late formation of F_5 folds is given by the folding of lamprophyre dykes at various localities (Plate 11B , pp. 78-9). At the Barns

(484368), horizontally slickensided surfaces developed during lateral movement on the Isle of Whithorn Fault (pp. 39-40) have also been affected by F_5 kink bands. F_5 is therefore assigned to the last period of folding which affected the area, and reasons will be given later to indicate that this occurred in Tertiary times (pp. 53, 61).

In the Whithorn area, the movement sense of the shear couples giving rise to F_5 folds is exclusively dextral. The steep axial planes trend approximately north-south, cutting across limbs and axes of earlier folds, and the axes therefore vary considerably in direction and amount of plunge, although the latter is usually steep (Fig. 13). One small part of the area (between Sliddery and Cruggleton Points) has been plotted separately (Fig. 13B) since the F_5 axes and axial planes appear to have a different orientation compared with the rest of the area, but the significance of this is uncertain.

4. Style of folding.

The presence on bedding planes of slickensides perpendicular to nearby fold axes shows that concentric folding has taken place during the formation of F_1 F_2 and F_3 folds. However, the strong axial plane cleavage developed in rocks affected by these folds, and by the larger-amplitude F_4 folds, indicates recrystallisation of material as a result of similar folding. Axial plane cleavage is most noticeable in the argillaceous beds, but a crude axial plane foliation may also be found in greywackes, especially in the hinges of the folds. Thin sections of foliated greywackes show recrystallised flakes of green chlorite with a parallel orientation in the matrix, which is interrupted around the larger clastic fragments (Plate 22B). The fragments are not granulated, and there is no sign of mobilisation of quartz. Thus the rocks appear to have reached the lower limit of chlorite grade regional metamorphism, in which the matrix is suffering recrystallisation, but the quartz grains remain intact. Such recrystallisation can only be the result of similar folding.

An attempt has been made to assess the relative importance of concentric and similar styles of deformation in F_1 F_2 and F_3 folds by measuring the variation in thickness of certain strata around fold hinges. Measurements were made directly in the field, and from photographs taken along the axes of folds displayed in sections perpendicular to the axial direction.

a) Field measurements.

In the field, thicknesses of various lithological units occurring in the same fold were measured at the axis and on the limbs. Limb measurements were made at a distance from the axis at which bed thickness had reached a consistent value. It was

CAPTION FOR FIGURE 20

A. Typical measurements taken from photographs of F_1 and F_2 folds.

(1) and(2). Bed thicknesses measured from the fold illustrated in Plate 3A.

(3). Curves represent theoretically derived percentage flattening of folds (see Ramsay 1962, p.315). The points (+) have been obtained from the fold illustrated in Plate 3A and figured here. The points (·) and X have been obtained from other folds, using the same technique.

B. Graphs of bed thickness on axes plotted against bed thickness on limbs to illustrate the different amount of axial thickening suffered by greywackes (+) as opposed to shales (·).

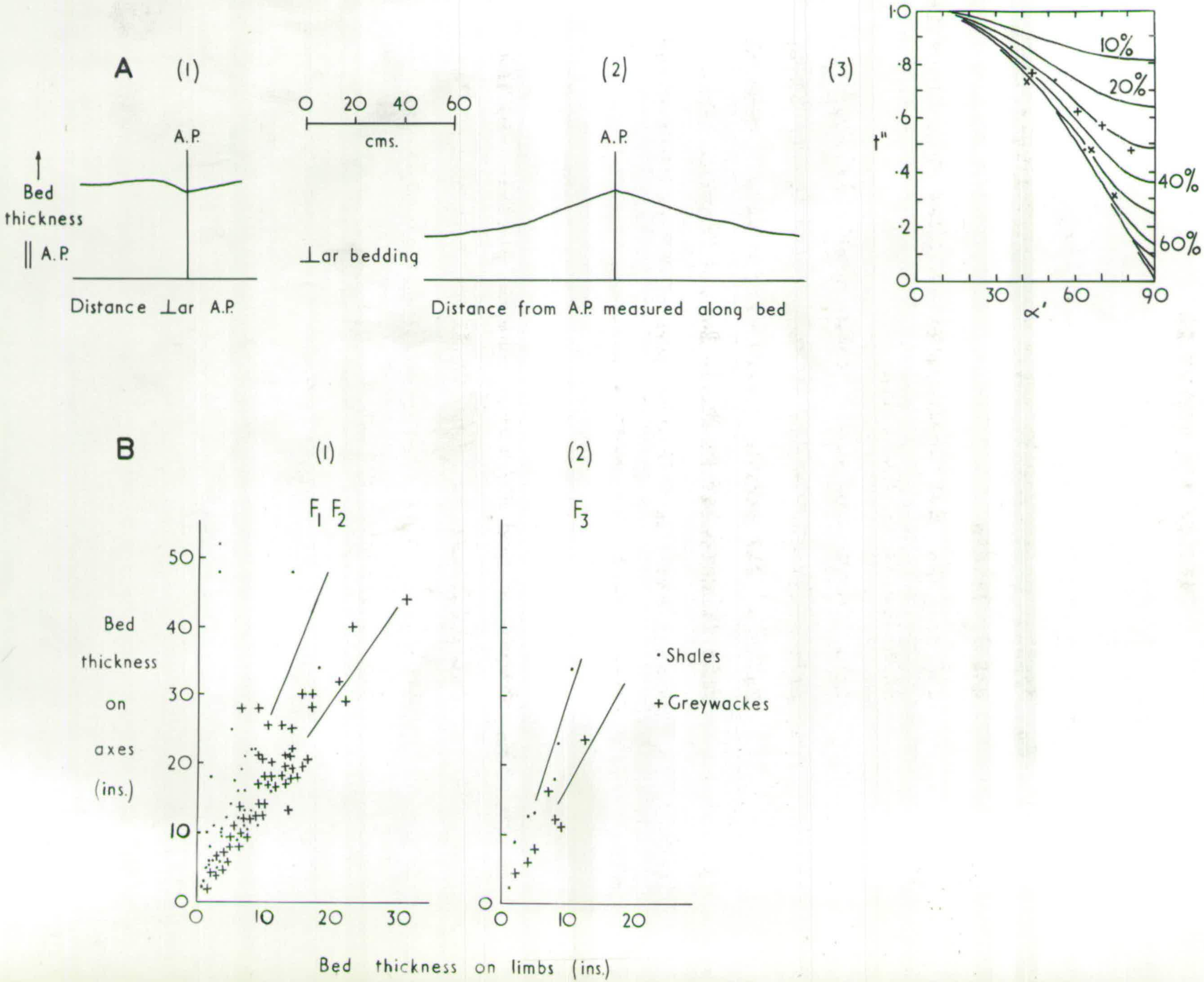

A
(1)
(2)
(3)
0 20 40 60
cms.
A.P.
Bed thickness ∥ A.P.
⊥ar bedding
Distance ⊥ar A.P.
Distance from A.P. measured along bed
t''
α'
10%
20%
40%
60%
B
(1)
(2)
F1 F2
F3
Bed thickness on axes (ins.)
Bed thickness on limbs (ins.)
· Shales
+ Greywackes

FIG. 20

found that fine-grained beds (shales, mudstones) show axial thickening amounting to about three times that of the limbs, whereas the greywackes show an average twofold axial thickening (Fig.20,B). The results suggest that all lithological types show some degree of similar folding in each of the fold phases considered. However, the more competent greywackes show the effects of deformation by similar folding to a lesser extent than the incompetent argillaceous beds.

b) Measurements from photographs.

More detailed measurements of bed thicknesses have been made from photographs of selected F_1 and F_2 folds (F_3 axes, being vertical, are not suitable for this purpose). Ideally, beds folded concentrically should not vary in thickness normal to the bedding, but Ramsay (1962, pp.313-6) shows that flattening by plastic flow following concentric folding will give rise to such a variation. The amount of flattening can be deduced by graphical means, and should be constant throughout the fold (Ramsay, Fig.7, p.315). This, however, is not the case for folds of the Whithorn area, for which the amount of flattening varies (Fig.20,A). Since the folds show undoubted evidence of bedding plane slip, it is suggested that the variation may be due to the occurrence of concentric and similar folding, together with flattening. In fact the plots of bed thicknesses parallel to the axial planes of F_1

and F_2 folds of the Whithorn area (Fig. 20,A) resemble quite closely those figured by Ramsay (1962) as examples of similar folds modified by flattening.

c) Conclusions.

There is evidence of deformation by concentric and similar folding and flattening by plastic flow in all lithologies during F_1 F_2 and F_3; this may also be applicable to the F_4 folds of larger amplitude. By comparison with the fine-grained beds, the greywackes were noticeably more affected by concentric folding, and more resistant to similar and flow folding. It is likely that F_1 folding began by concentric deformation of the greywackes, accomodated by flow folding in the still-plastic intervening shales. In this way the early concentric folding probably persisted in depth, which would have been impossible had all the strata been concentrically deformed. Later, the folds in the greywackes were modified by flattening, and deformation continued largely by a modified similar process in all lithologies.

3. Faulting.

1. Introduction.

The excellent coastal exposure shows that the area has been profoundly affected by a great variety of faults, of which about 1400 have been measured (Fig. 22). In many cases measurement was limited to the orientation of the fault plane, since it is frequently impossible to deduce throw in sediments which are so lacking in distinctive horizons. On account of this, and the complex nature of both folding and faulting, only small throws can be detected, although it is likely that faults of considerable throw are also present.

Wherever linear slickensides were found on faults, their pitch on the fault plane was measured. While a single measurement of this nature can hardly be considered a reliable indication of fault throw, it is suggested that a large number of such observations can give a good estimate of movement direction. In the Whithorn area the situation is complicated by a high prevalence of reactivated shears, ie. those with more than one set of slickensides. In Fig. 15A histograms show the proportion of multi-slickensided surfaces for the different typ es of fault.

Additional evidence in support of reactivation can be obtained by calculating values of ϕ , (the angle of internal friction), for fault planes with oblique slickensides. (Williams

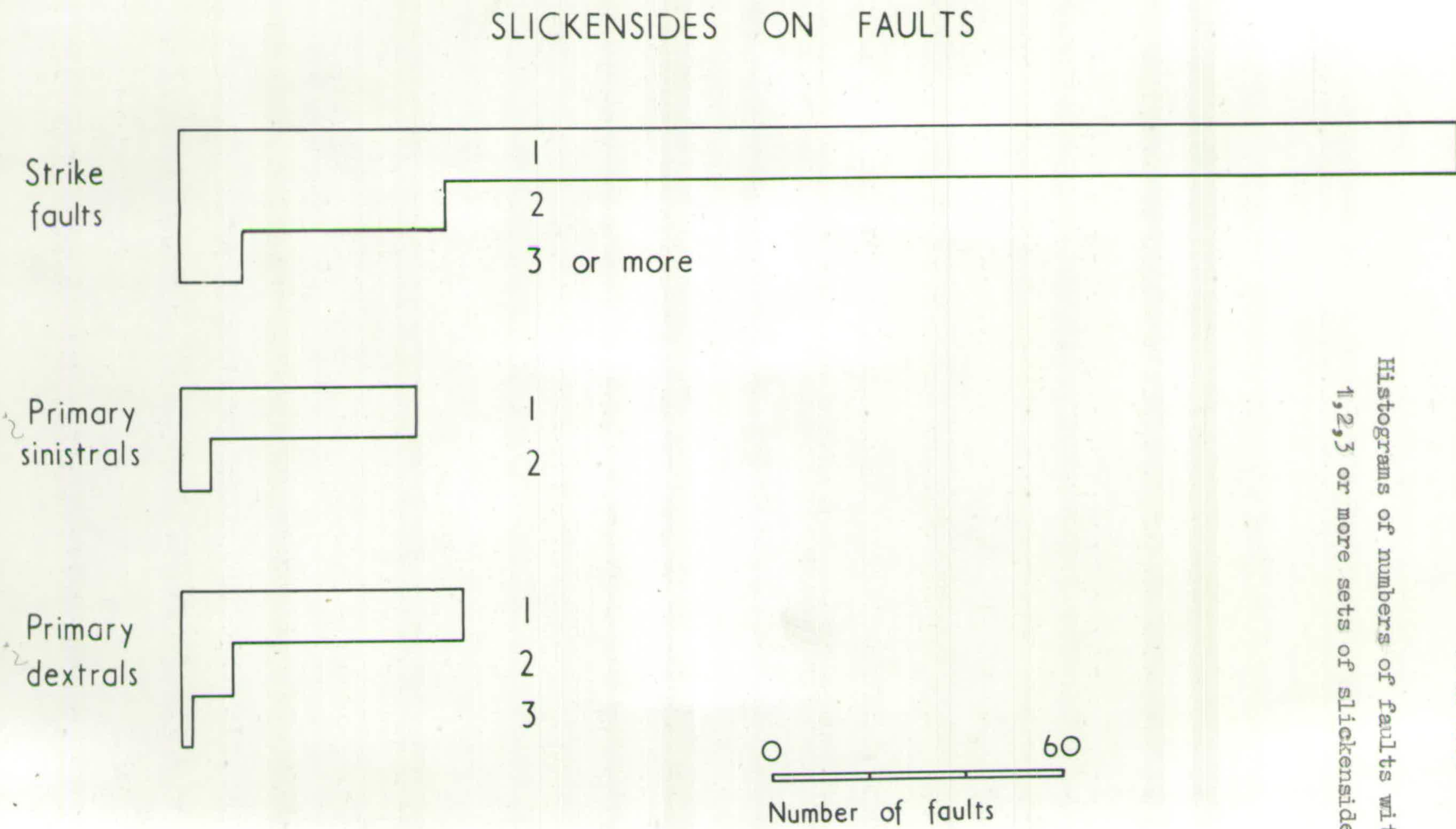


FIG. 15A

Histograms of numbers of faults with 1,2,3 or more sets of slickensides.

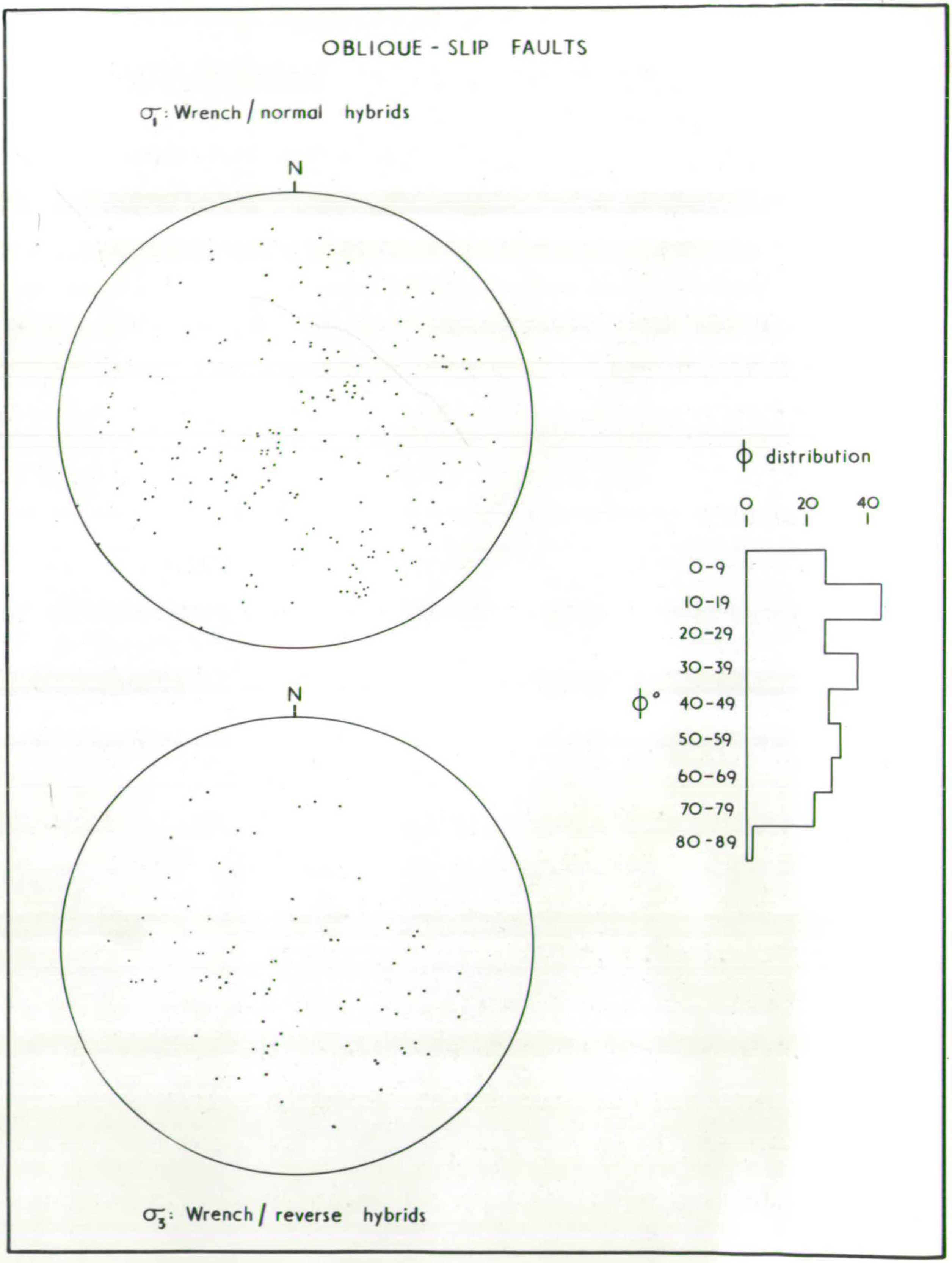
(1958) outlines a stereographic method for studying oblique shears, and in a later paper (1959) applies the method to faults in the Girvan district of Ayrshire. His results show a distribution of ϕ (1959, p .652) with a prominent mode of about 50% of calculated values about 35°, the angle which would be expected in primary shears. He therefore concludes that the remaining 50% of the shears considered have different values of ϕ because of decreased internal friction due to reactivation of pre-existing fault planes.

In the present work, all shears with slickensides pitching between 10° and 80° have been analysed by Williams' stereographic method; the distribution of ϕ obtained is shown in Fig. 15 . This almost random ϕ distribution may be explained in one of two ways. Either Williams' method is inapplicable to the Whithorn area, or else the distribution reflects a very high degree of reactivation - perhaps affecting 80% of faults present. In this case, the latter explanation is preferred.

Drag folds associated with fault planes are not common in the Whithorn area, and their reliability as indicators of slip on faults has been questioned by Ramsay (1962, p.520). Slickensides, and consistent curvature of strata adjacent to fault planes have therefore been preferred as evidence of fault displacement.

The relative dating of faults has been based on cases where a clear displacement was seen, and not on single terminations of one fault against another. To show that fault A is older than

FIG.15


OBLIQUE - SLIP FAULTS
σ_1: Wrench / normal hybrids
N
N
σ_3: Wrench / reverse hybrids
ϕ distribution
0
20
40
$\phi°$
0-9
10-19
20-29
30-39
40-49
50-59
60-69
70-79
80-89

fault B, it is necessary to find the continuation of A displaced by B. It was found that relative ages of faults deduced in this way were consistent with data derived from intersections of faults with minor intrusions.

Various stereographic methods were used in an attempt to analyse the fault data: poles to fault planes, plunge of slickensides, and calculation of principal stress directions from slickenside pitch (Williams 1958, 1959 pp.650-1). When all types of faults were plotted together, the result in each case was a "plum-pudding" distribution which could not be easily interpreted. It was therefore necessary to divide the faults of known movement into a number of categories, and to assume that other faults with similar orientation and slickenside trend could be assigned the same movement sense. Any such division is to a certain extent arbitrary. Thus shears with slickensides pitching up to 30° have been included within the wrench fault category. Strictly speaking they are oblique-slip faults, but are included as wrench faults because strike-slip movement has predominated.

These fault categories, with their modal characteristics, are as follows:

Strike faults: Vertical 045*

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* The term strike fault is used as a convenient description for an important group of faults with a modal trend parallel to the N.E.-S.W. regional strike induced by the Main fold phase. Individually, many of these faults are sub-parallel rather than parallel to the strike.

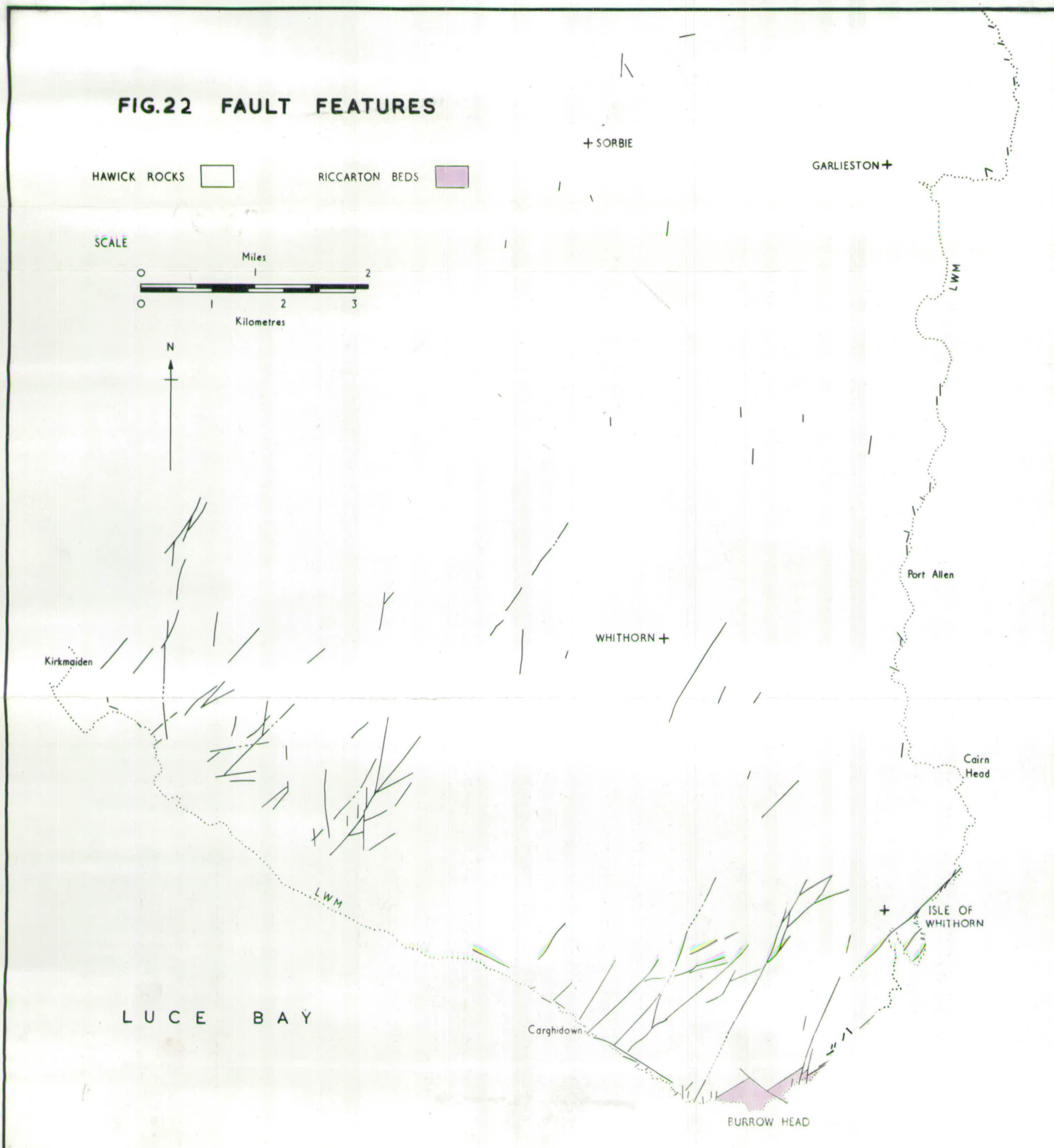


FIG.22 FAULT FEATURES
HAWICK ROCKS
RICCARTON BEDS
SCALE
Miles
0
1
2
0
1
2
3
Kilometres
N
SORBIE
GARLIESTON
LWM
Port Allen
WHITHORN
Kirkmaiden
Cairn Head
LWM
ISLE OF WHITHORN
LUCE BAY
Carghidown
BURROW HEAD

1st order dextral faults: vertical 110

1st order sinistral faults: vertical 005

Thrust faults: 15°N 110

In certain cases, faults could not be definitely assigned to a particular type, or had contradictory characteristics, such as dextral displacement with trend parallel to primary sinistrals. Most of these "anomalous" cases are thought to be reactivated shears, and will be discussed separately, after the main types.

It has been found that the methods of plotting poles to fault planes and plunge of slickensides (for the various fault types separately) are both simpler and more instructive than Williams' technique of deducing stress axes for oblique-slip faults. The results of applying the latter technique to the Whithorn area (or to sub-areas) are practically unintelligible (Fig. 15). This is probably due to the fact that Williams' method is not applicable to reactivated shears (see Bott 1959), which, as already stated, are very prevalent in this area (p. 35).

2. Strike Faults.

Faults parallel or sub-parallel to the regional strike are important throughout the area, and are especially noticeable as linear features on the aerial photographs. The orientation of

PLATE 12.

A. The Isle of Whithorn Fault. The feature formed by this fault passes from the foreground, through the village, and up the valley beyond.

B. The Burrow Head Fault occupies a small zone in the centre of the picture, but does not produce a feature. To the left of the picture occur red beds of the Hawick Rocks (H), and to the right are graptolitic horizons of the Riccarton Beds (R).

A

B

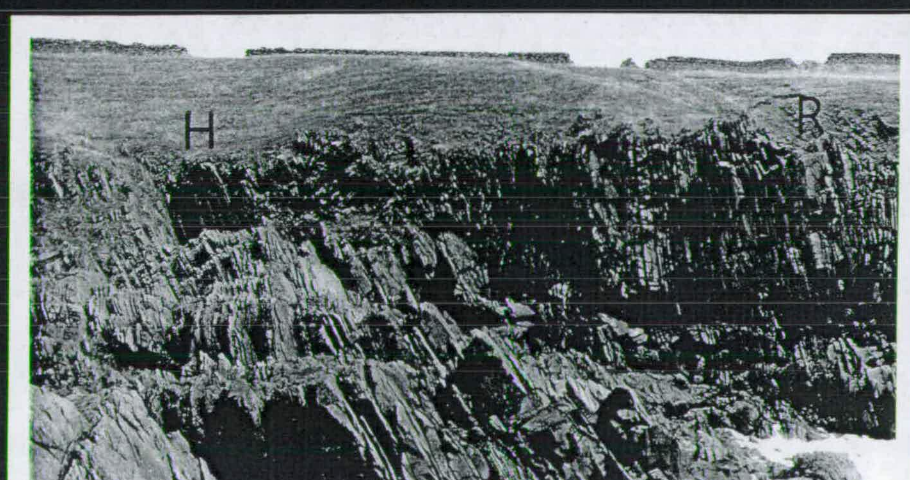
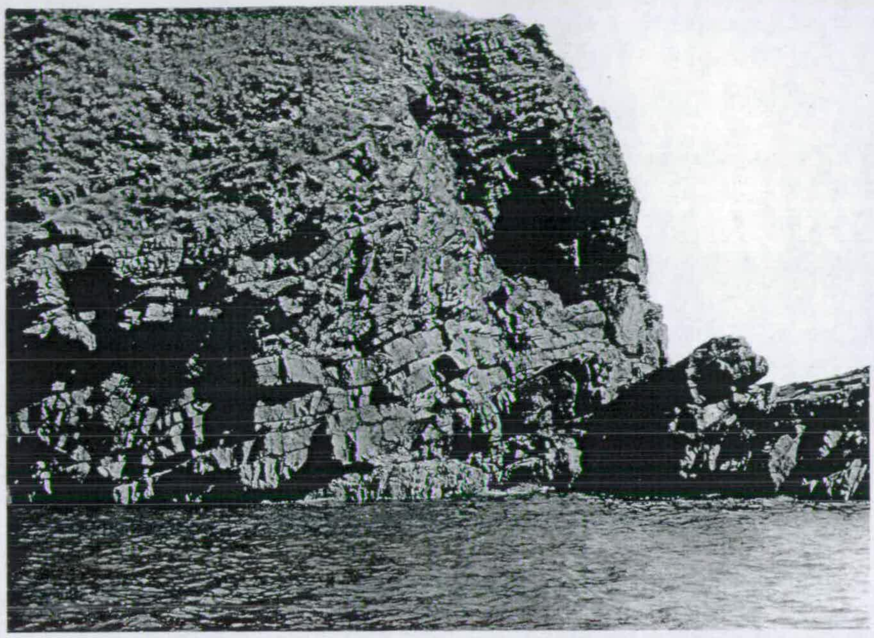


PLATE 13.

A. Thrust plane associated with overturned F_1 folds (Cruggleton Point).

B. Dyke intersection, showing a clear displacement of a hornblende lamprophyre (X) by a biotite - lamprophyre (Y), near Physgill.

A



X

B

Y

these features has been measured by a method designed to eliminate photographic distortion*, and the results are shown in Fig. 17. They are expressed in terms of aggregates of miles for each orientation, the fault features being easily distinguished from bedding strike features by their persistence for hundreds or thousands of yards, whereas bedding features may be measured in tens of yards only.

It can be seen that two approximately equal maxima for fault features are present at 005 and 045, which correspond to the primary sinistrals and to the strike faults respectively. There is no doubt that the inland strike features have been formed from strike faults, since in several cases they can be traced to the coast, where the plane of the fault responsible can be found. The best examples of this may be seen on the west coast at Devil's Arch (438349), Carghidown (435351) and Lobbocks (433352), and on the east coast at Isle of Whithorn. The latter feature can be traced for over a mile while the Isle of Whithorn Fault itself and numerous associated shears can be seen between The Barns (484368) and Stein Head (486371), (Plate 12A).

Strike faults, as measured on the coast, vary symmetrically in orientation about a mode of vertical 045. Where

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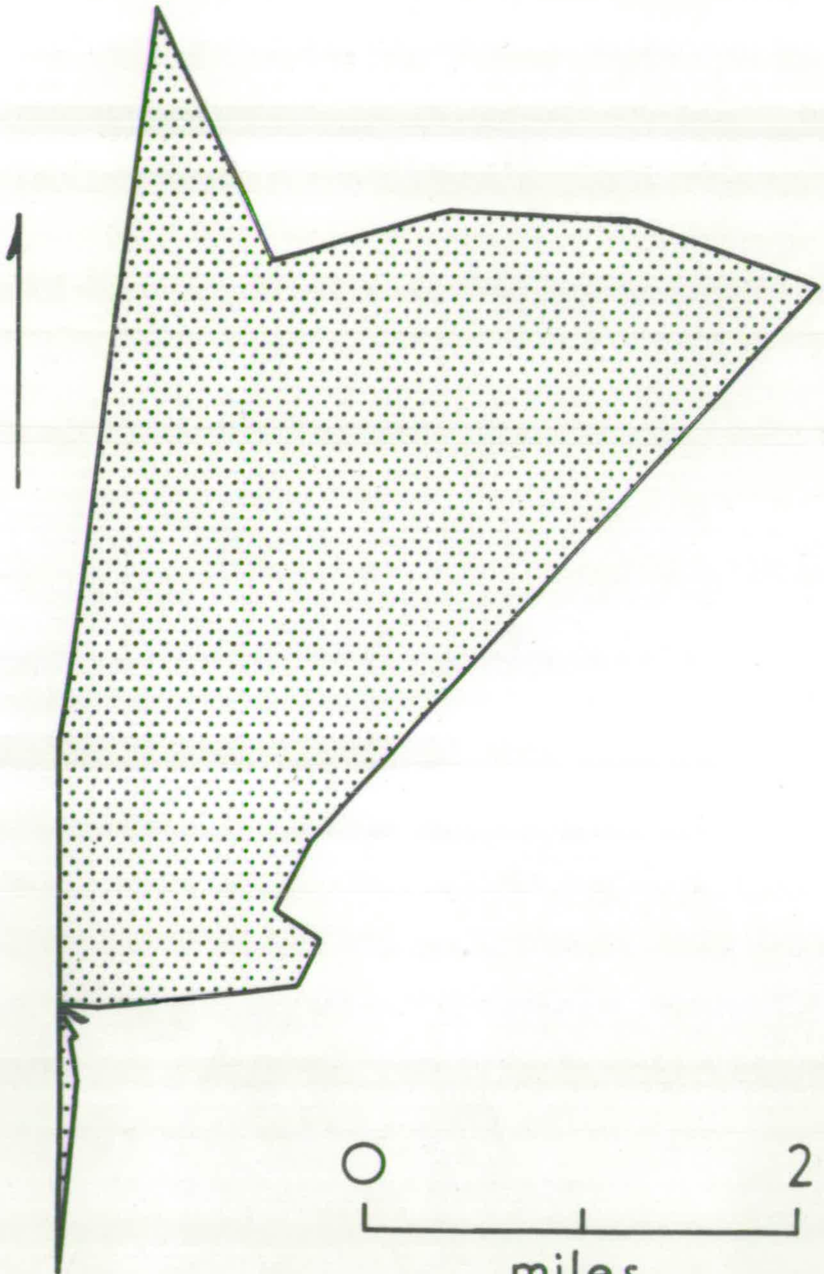
* A tracing (including field boundaries) was made from the Ordnance Survey 6" maps, on which the linear features from the aerial photographs were inserted field by field, avoiding distortion by reorientating the tracing for each field.

FIG. 17



Linear features from aerial photos

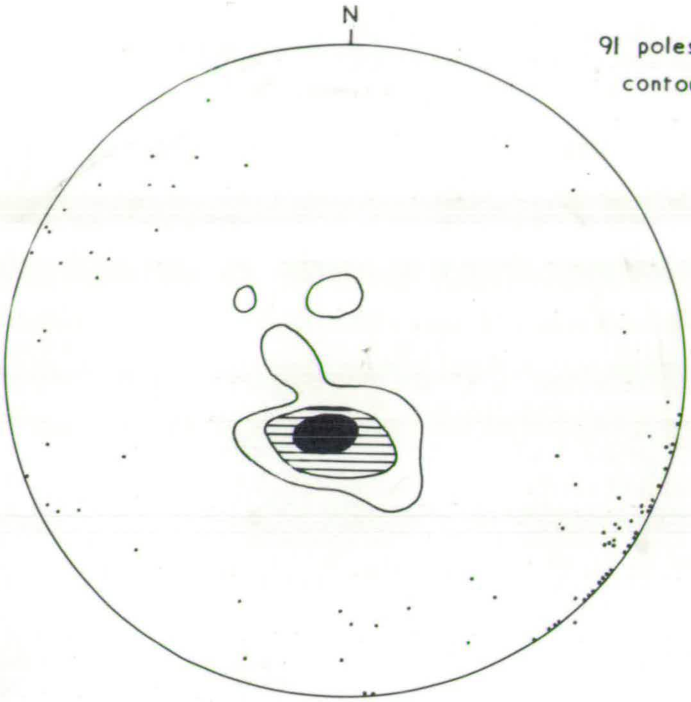
displacement of sediments has been observed, it is predominantly dip-slip (but it should be noted that lateral displacement cannot easily be detected in strike faults). Out of 40 observed displacements 26 showed reverse movement and 14 normal, but many of the planes approximate to the vertical, in which case the distinction between normal and reverse movement is not very significant. Thus the ratio of southward as opposed to northward downthrow (89:69) is probably a more meaningful expression of the data. To this slight predominance of southward downthrow must be added the throws inferred on stratigraphical grounds for major faults, which are mostly thought to have considerable downthrow to the south.

Lateral movement on strike faults may be seen in the displacement of features oblique to the strike, such as dykes and other faults. Of these lateral displacements, sinistrals exceed dextrals by 59 to 12. Lateral displacement cannot usually be seen on the major strike faults (presumably because it is too large), but the arrangement of splays to the Isle of Whithorn Fault suggests that it has moved sinistrally (Fig. 18).

Slickensides on the planes of the strike faults have two preferred orientations: one horizontal at 045, the other plunging 80° to 040 (Fig. 16). Of these, the slickensides of the former set are far more numerous than the latter, which suggests an early dip-slip phase of movement, followed by a predominantly strike-slip one. The different sets of slickensides may sometimes

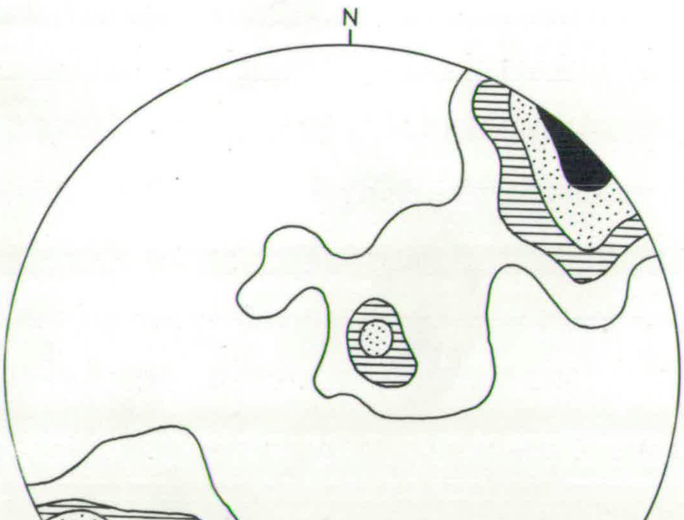
FIG. 16

Plunge of slickensides on thrusts



91 poles to thrust planes
contoured at 5, 10, 15%

Plunge of slickensides on strike faults



Contour intervals
1, 3, 5, 10%

320 plunges

be seen together on the same fault plane, as for instance on the Isle of Whithorn Fault and its associated splays at the The Barns. Here horizontal slickensides are almost universal (and are even found on bedding planes adjacent to the fault), but faint steeply-pitching slickensides are occasionally found, especially in irregularities of the fault planes. It is therefore concluded that the strike faults, moving originally with essentially dip-slip displacement, were later reactivated mostly as sinistral wrenches.

It is difficult to explain dip-slip movements on vertical fault planes in terms of stress systems without assuming that subsequent tilting has brought the faults to their present attitude*. Thus it seems unlikely that the present vertical mode of these faults is an original feature, and it is therefore impossible to deduce whether they were normal or reverse in the first instance.

The 20% of reactivated strike faults which show a dextral displacement cannot be 2nd order shears or splays to the sinistral reactivation, since in either case they would have the same displacement (McKinstry 1953, p.402, Anderson 1951, p.167). They are probably the result of reactivation under a different stress system, and will be considered as such under a later section (pp. 45-6).

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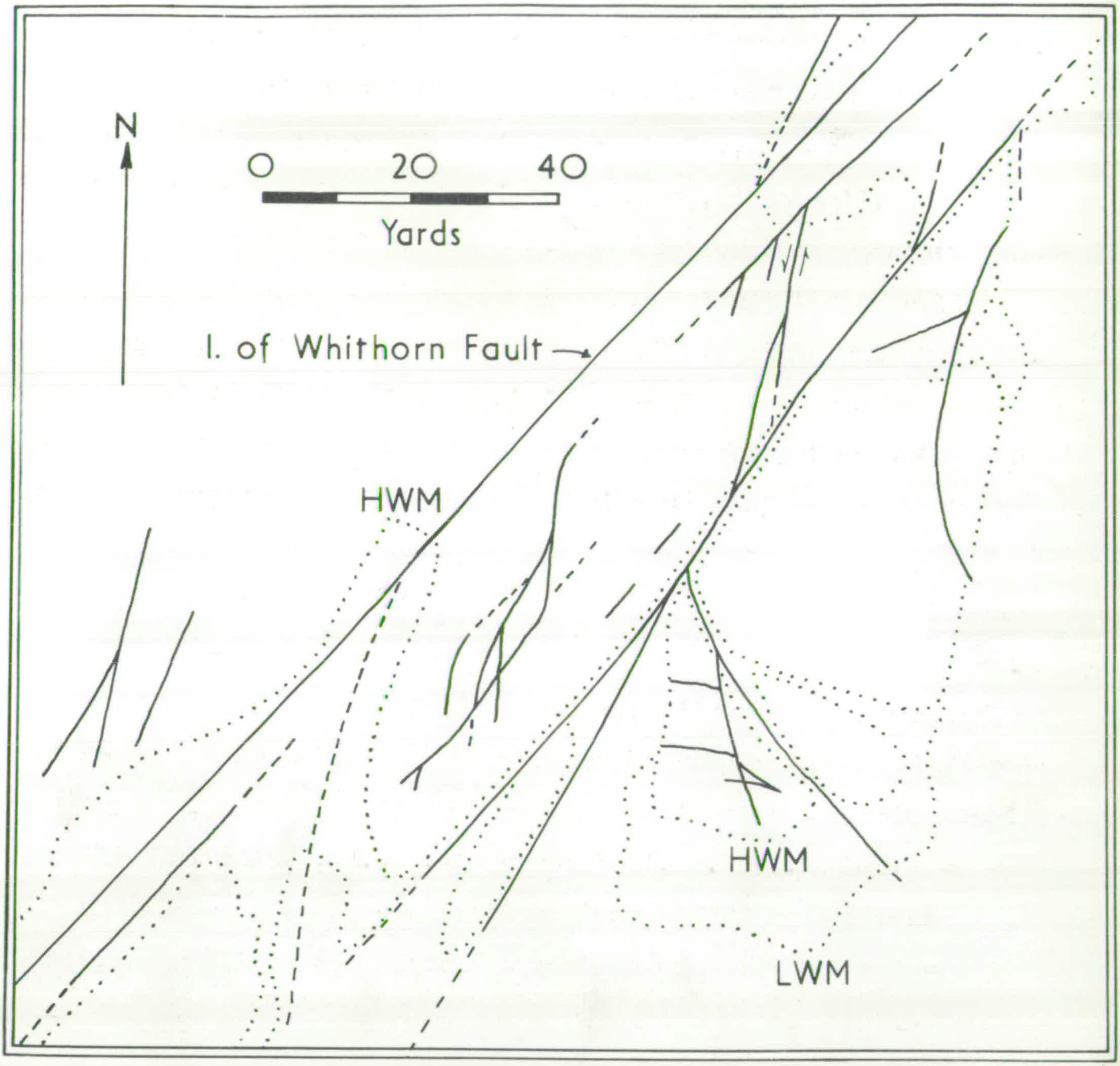
* Or alternatively that the principal stress directions were not parallel and perpendicular to the horizontal.

FIG. 18



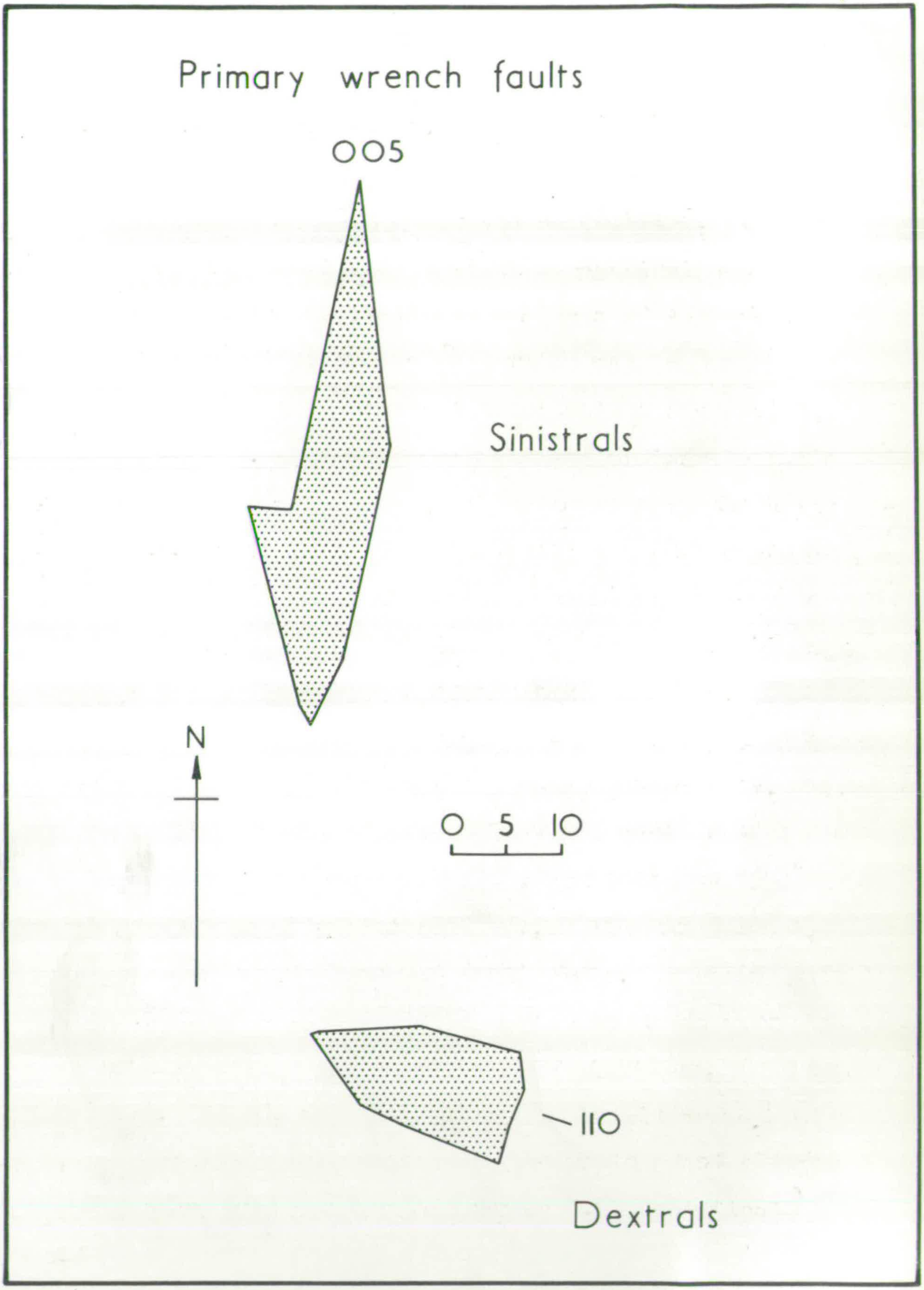
Map of the Isle of Whithorn Fault and associated shears at The Barns.

3. Primary Wrench Faults.

As indicated in the introduction to faulting, sinistral and dextral faults with modal orientations of vertical 005 and vertical 110 respectively are important features of the area. They form a conjugate set of shears from which can be deduced a stress system that is entirely compatible with that responsible for the Main fold phase. For both dextrals and sinistrals there is, as would be expected, a strong slickenside mode at the horizontal ~~(Figs.)~~. However, steeper slickensides are also present, and the occurrence of more than one set of slickensides on some of these faults shows that reactivation has taken place, although to a lesser extent than in the case of the strike faults.

At a number of places on the south-west coast the primary dextrals form prominent features parallel to the shore (Fig. 22). For instance a fault which displaces a thick red shale band 200 feet dextrally near Castle Feather (447343) persists for 1000 yards along the coast to Mary Mine (439348), which was formerly worked for copper developed along the fault plane. Another dextral fault at Physgill forms a cave (423359) which passes through the headland and across the bay called Bloody Neuk (421361), a distance of over 400 yards. Other, smaller faults are found parallel to this shore, and the rectilinear nature of the whole coast between Loch Ryan and Burrow Head (as may be seen on H.M. Geological

FIG. 19



Survey $\frac{1}{4}$" Sheet 16), may have been largely determined by a series of dextral faults.

By contrast with the dextrals, the sinistrals have little control over the coastal topography, although they do promote the formation of coves transverse to the coastline at Castle Feather and Cruggleton Lodge (485436). At first sight it therefore seems anomalous that strong topographical features should be formed inland along sinistral fault-lines, whereas the dextrals appear to have little influence on the inland relief (Fig. 17). The dextral faults are, however, almost perpendicular to the direction of flow of the Quaternary ice-sheet (Charlesworth 1926), while the strike faults and primary sinistrals both lie at small angles to this direction. Thus the sinistral and strike faults would tend to be gouged out by the ice, while the dextral fault features were largely obscured.

4. Thrust faults.

Low-angle thrust faults are fairly widely distributed, but are especially common between Sliddery Point (486441) and Palmallet Point (484422) on the east coast. This locality is also marked by the recumbent nature of the F_1 folds, which here reach their maximum degree of overturning (see pp. 19-20 and Fig. 30). The thrusts are intimately associated with these folds, lying parallel or sub-parallel to their uninverted limbs, and showing thrusting in the direction of overturning of the folds (ie. towards the south-east), (Plate 2B). It is therefore suggested that thrusting commenced towards the end of or immediately after the formation of F_1 folds, under the influence of the same stress conditions.

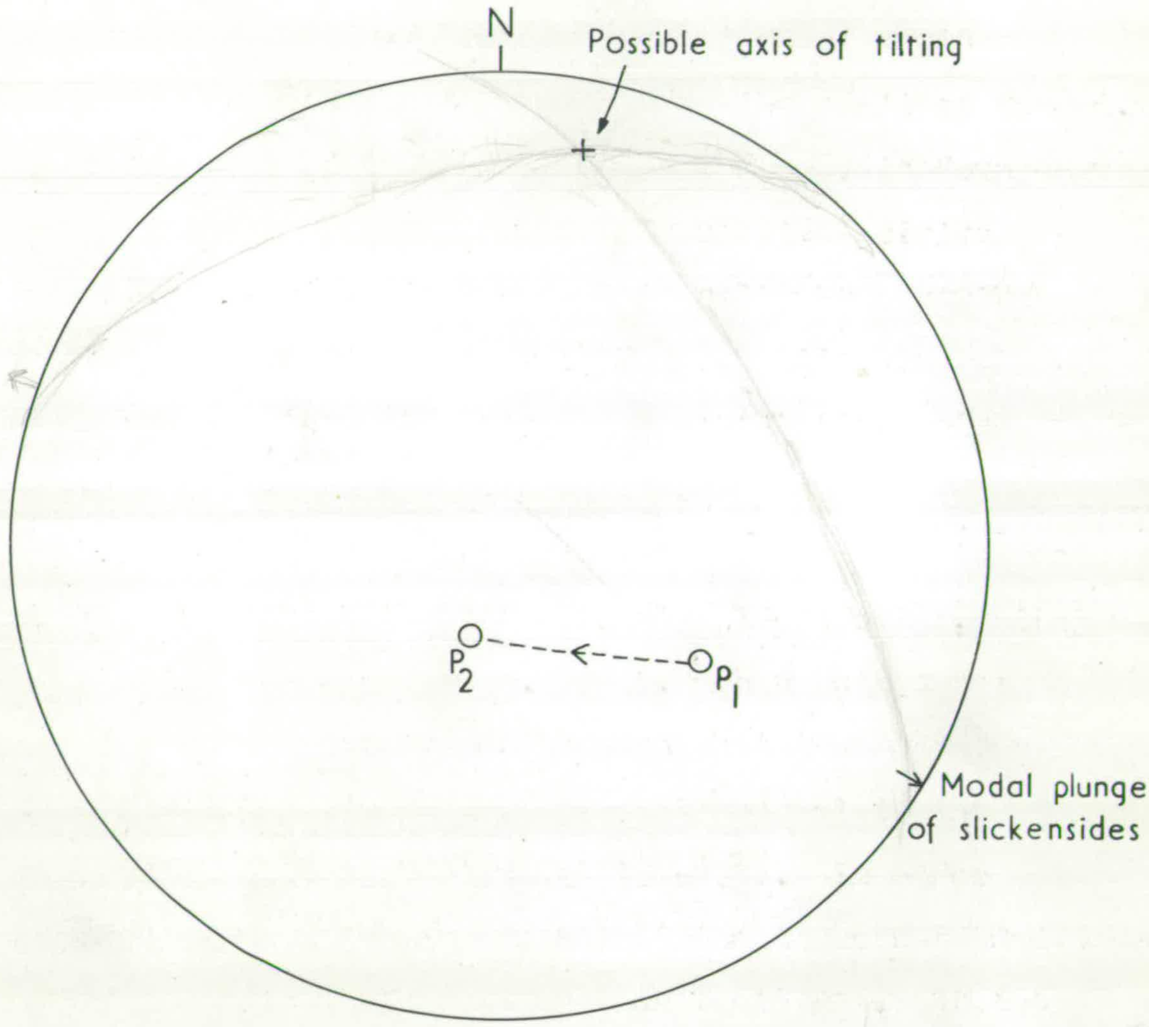
The evidence obtained from intersections of various types of fault also suggests that thrusts were the earliest formed. A thrust 500 yards north of Cruggleton Point (485428) is downthrown to the south by dip-slip on an approximately vertical strike fault ~~(Plate)~~. A thrust displaced sinistrally by a strike fault may be seen near Castle Feather (447343), while several examples of thrusts displaced by primary wrench faults, both sinistrals and dextrals, are known.

The distribution of poles to thrust planes and plunges of slickensides on thrusts both show a fairly wide scatter, with a reasonable mode in each case (Fig~~s~~. 16). When both these modes are considered together it can be seen that the mode for thrust plane poles (80° towards 200) is nearly normal to the modal plunge of slickensides (horizontal 125-305). In other words, the present orientation suggests that the thrusts tended to move parallel to their strike rather than their dip. If this were an original feature, it would indicate a rotated stress system in which σ_2 and σ_3 were tilted out of their normal positions (horizontal and vertical respectively) about σ_1.

FIG. 21

P_1 : Original mode of thrust poles

P_2 : Present " " "



Suggested mode of tilting of early thrust planes.

A more likely explanation is that the thrusts have been tilted since they were formed, so that their present unusually low dip and apparent strike-slip movement are not original. If an original dip of 40° is assumed parallel to but in the opposite direction to the movement sense indicated by the slickensides (ie. towards 305), then tilting about an axis plunging 10° NNE could have produced the observed result (Fig. 21). This suggests that tilting during F_2 folding would be the most likely cause.

The association of irregular quartz-mineralised thrusts with F_4 folds has already been mentioned (p. 28). This association shows that the thrusts are later than those formed during the Main fold phase, and elsewhere late thrusts are seen to cut F_3 axes and a number of Caledonian dykes. Because of irregularity the attitude of the late thrusts is not easily measured, but they are approximately parallel to the axial planes of the F_4 folds with which they are associated (Fig. 13), Plate 10B).

5. Reactivated faults.

Under this heading will be discussed faults which have the same orientation as one or other of the primary fault types, but show a different displacement. None of these are common in the area and the most reasonable explanation of their presence is the reactivation of primary shears under different stress conditions. Most of these may be termed wrench-reactivated faults, since the secondary movement has been predominantly strike-slip. The widespread sinistral reactivation of strike faults has already been discussed (pp. 39-40), but these faults also show occasional dextral reactivation. Faults with attitudes corresponding to primary sinistrals and dextrals but with the opposite movement senses are also considered to be wrench-reactivated shears. A dextrally-reactivated primary sinistral fault gives rise to an important topographical feature which extends from Thief's Hole to Cutreoch (467357), and displaces the Hawick/Riccarton boundary dextrally (Fig. 22). A parallel feature extends from Cutcloy (452350) to Drummoral (462362), but in this case there is no evidence of displacement.

The distribution of values of the angle ϕ obtained from oblique-slip shears shows that the majority of these shears arose by reactivation of pre-existing faults (see pp. 34-5). It is probable, therefore, that the occasional steeply-pitching slickensides on primary wrench faults were formed by oblique-slip reactivation. Such reactivation may also have affected the strike faults, and may be responsible for the spread of slickensides between the two modes corresponding to primary dip-slip and secondary strike-slip (Fig. 16).

4. Intrusive Phases.

1. Introduction.

The igneous rocks of the area were studied in relation to folding and faulting as an aid to the interpretation of the tectonic history. The interest in this section is therefore primarily structural rather than petrological.

All intrusions within the area may be classified as dykes (many of which are largely concordant), none exceeding 30 feet in thickness. They are divisible into two distinct groups (Caledonian and ?Tertiary) on the grounds of petrology and age (Read, 1926). In the account which follows a simple classification is used; more detailed petrographic descriptions and some petrogenetic conclusions are given in Appendix I (pp. 113-8).

2. Caledonian intrusive phases.

A group of dykes containing varying proportions of quartz, acidic felspars and ferro-magnesian minerals have been classified as porphyrites and assorted lamprophyres by various authors (Blyth (1949), King (1937), Read (1926), Reynolds (1931). The Caledonian age of the dykes has been assessed on geographical and petrological affinities to the Caledonian plutonic bodies,*

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* Age determined at 386 ± 8 million years by potassium-argon dating (Kulp et al, 1960).

Lt. Dev?

and on their absence from post-Silurian strata.

In the Whithorn area the earliest of these intrusions are light-coloured, pink-weathering felsites, which are poor in ferro-magnesian minerals, and are frequently non-porphyritic. In view of the latter feature, and the confusion introduced by Reynolds (1931), who referred to certain coarse-grained lamprophyres as "hornblende-porphyrites", the term felsite is preferred to porphyrite. The alternative terms microgranite and microgranodiorite are considered too precise to be applied to these rocks.

The felsites were mostly intruded as dykes largely parallel to the strike, which sometimes cut across, and therefore post-date the F_1 folds, but are older than the primary wrench faults. Felsite dykes oblique to the strike have been displaced laterally by strike faults, and in one instance a felsite dyke has been moved vertically by a strike fault*.

Felsites are cut by lamprophyres at two places: The Lick (468346), and 150 yards south of Lobbocks (433352), while a felsite which has been metamorphosed by a biotite-lamprophyre may be seen at Carghidown (435351). Felsites are therefore the

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* Evidence of an intrusion being older than a fault is based on the shearing of the former, and therefore excludes the possibility of mistakenly identifying a dyke as older if it partly follows the fault plane.

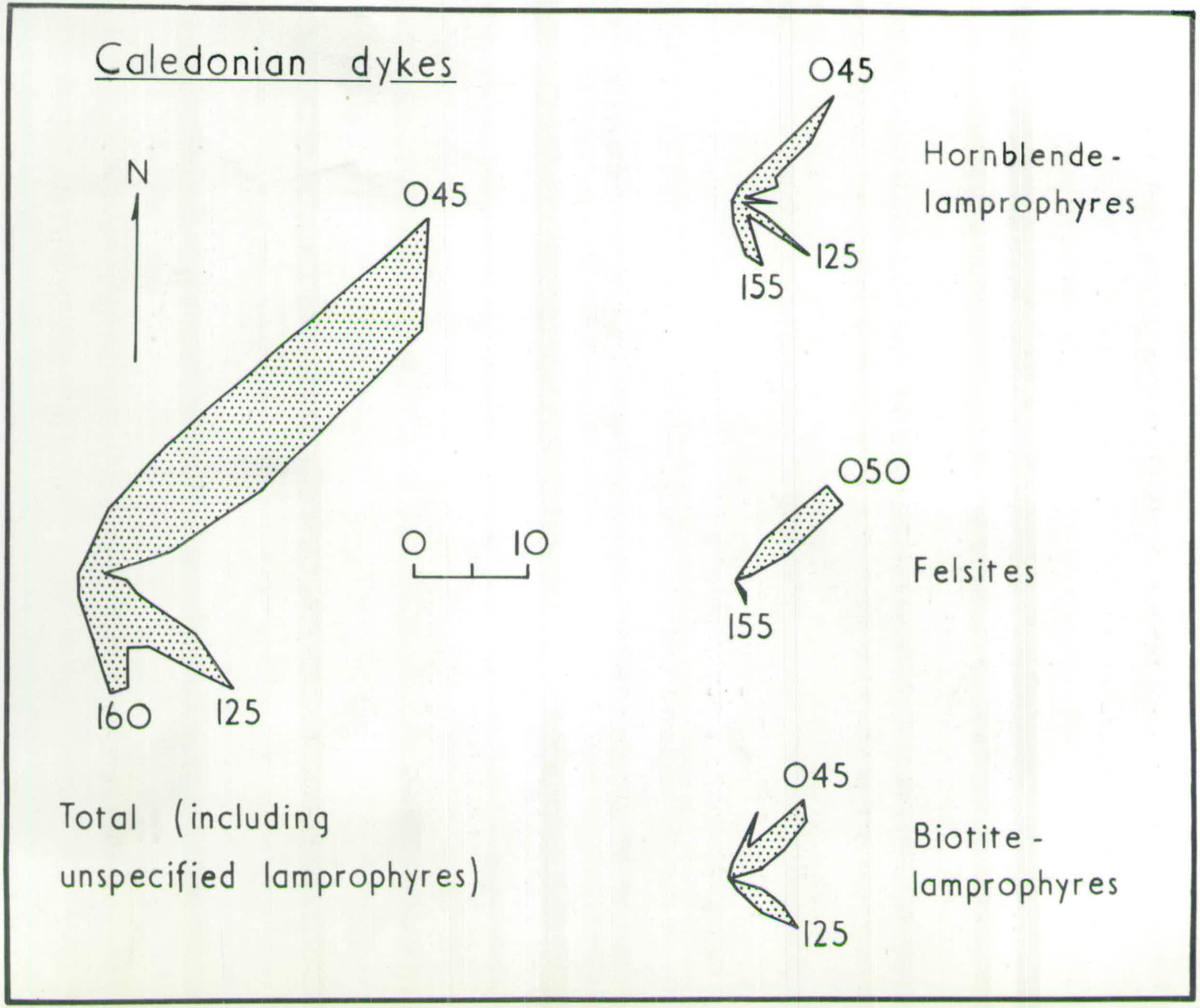
oldest of the intrusions. No definite evidence has been found to suggest that there was more than one period of felsite intrusion (as has been found elsewhere in the Southern Uplands - Holgate, 1943), but this lack of evidence is probably due to the small number of felsites in the Whithorn area. A 20 ft. felsite dyke at Shaddock Hole appears to be unaffected by F_3 folding, but this may be due to the massive nature of the dyke, rather than post-F_3 intrusion.

The most numerous intrusions of the area are those richer in ferro-magnesian minerals, here divided simply into biotite - and hornblende-lamprophyres. Both these types vary considerably in properties (Appendix I), and the structural evidence indicates that the periods of intrusion were partly synchronous, or alternatively that there was more than one intrusive phase for at least one of the types.

Biotite-lamprophyres are cut by hornblende-lamprophyres at Devil's Arch (438349) and at a locality 100 yards north of Rock of Providence (443345). In addition, biotite-lamprophyres have been affected by F_3 folding, whereas some of the hornblende-lamprophyres post-date it. At Monreith Black Rocks (358407) a biotite-lamprophyre lies parallel to the axial plane of F_3 folds, and has been sheared in the same plane. At Devil's Arch a biotite-lamprophyre sheet has been folded together with the sediments in a vertically-plunging F_3 axis, and exhibits a crude foliation parallel to the axial plane of the fold. In thin section this foliation can be seen as shears or 'kink bands' crossing the biotites transversely. By contrast, a hornblende-lamprophyre at Shaddock Hole (477397) cuts across two F_3 axes.

The evidence given above seems to demonstrate the earlier intrusion of biotite-lamprophyres. However, at the eastern end of Port Castle Bay (426357) a hornblende-lamprophyre is cut and displaced dextrally by a biotite-lamprophyre which is quite unaffected by shearing (Plate 13B). A few yards to the east another hornblende-lamprophyre appears to cut the same biotite-bearing dyke, but the intersection cannot be definitely confirmed, since it occurs at the edge of a precipice. This indication of two phases of hornblende-lamprophyre intrusion is tentatively confirmed by the difference between the two hornblendic types: the early one contains small anhedral altered hornblendes, while the later one bears large relatively unaltered euhedral hornblendes (Appendix I). The sequence of lamprophyric intrusive phases is therefore thought to be as follows:

1. Lamprophyres with "embryonic" anhedral hornblendes, largely altered.
2. Biotite-lamprophyres.
3. F_3 folding.
4. Lamprophyres with "mature" euhedral hornblendes, frequently unaltered.



Caledonian dykes
N
045
160
125
0
10
Total (including
unspecified lamprophyres)
045
Hornblende -
lamprophyres
125
155
050
Felsites
155
045
Biotite -
lamprophyres
125

FIG. 23

All types of Caledonian intrusions tend to be orientated parallel to the regional strike of the sedimentary rocks* (Fig. 23, primary mode 045). Lamprophyres of both types form a second mode at about 125, while hornblende-lamprophyres and a few felsites make up a third mode at about 155.

The main mode at 045 is probably due to dykes of all types occupying tensional joints formed as a sequel to the main fold phase, but in some cases the magma has exploited the planes of strike faults. The mode at 125, consisting solely of lamprophyres, is probably due to these dykes exploiting primary dextral fault planes. In fact, of the lamprophyres with this orientation, five (all biotite-bearing types) do show a dextral displacement of the sediments on either side. In one of these cases, the dyke rock has filled in irregularities in the dyke wall caused by slip on beds curving towards the plane of the fault. Since the dyke rock is not sheared, it is suggested that the magma was fluid at the time of movement along the fault, and acted as a lubricant. This exposure (Fig. 24A), is on the west coast, 150 yards south of Lobbocks and suggests that the biotite-lamprophyres were intruded at about the time of formation of the primary dextral faults.

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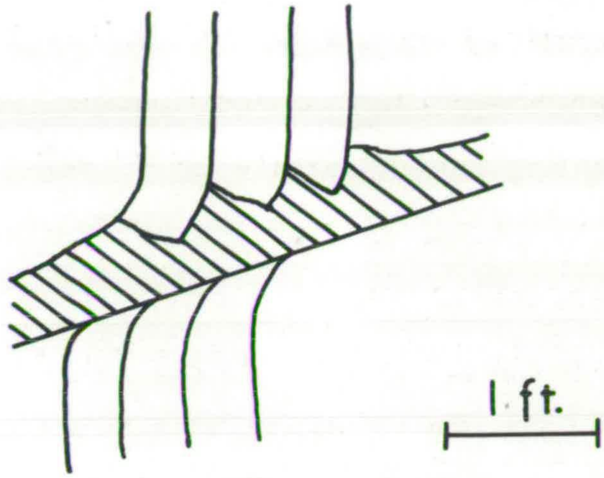
* This mode is somewhat exaggerated, because by comparison with the coast, intrusions exposed inland tend to be very largely strike-parallel. This is probably due to erosional factors.

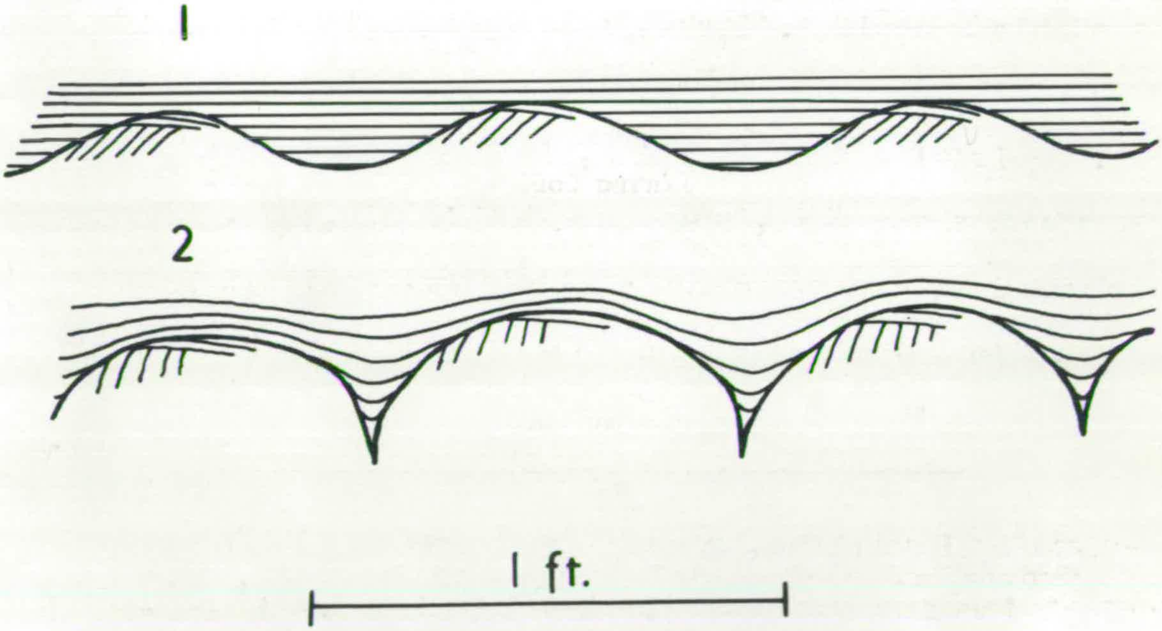
FIG. 24

A



Biotite lamprophyre dyke intruded parallel to a dextral fault.

B



Suggested mechanism for loading of transverse ripples.

The third dyke mode, at 155, can probably be related to ac joints formed during the Main fold phase, but not exploited by intrusions until later. The situation is not entirely clear, however, because the 155 direction is not precisely perpendicular to the Main fold trend, and there seems to be no reason for the biotite-lamprophyres avoiding it.

Reynolds (1931) and Blyth (1949) have drawn attention to sheared Caledonian dykes in Co. Down and Kirkcudbrightshire respectively. Reynolds considers the sheared dykes to be an older series, formed by crushing perpendicular to the dykes, and distinct from a series of non-sheared dykes. Blyth does not draw the same age-distinction, and attributes shearing to movement parallel to the dyke walls.

In the present study, a limited number of sheared dykes have been found, which (within the limits imposed by the high degree of alteration) show close petrological similarities to those described by Reynolds. However, it is considered that the shearing can be attributed to a number of different causes, and not to one alone.

Biotite-lamprophyres at Monreith and Devil's Arch (see p. 48) have been sheared in the formation of F_3 folds; approximately parallel to the dyke wall in the former locality, and in the latter, transversely. Sheared dykes of a different nature are found with attitudes corresponding to the modes of strike, dextral and sinistral faults. These are thought to have been intruded into the planes of weakness left by the faults, and sheared by the re-occurrence of wrench movement on the faults, in a similar way to that described by Blyth (1949). However, there are also several examples of dykes bounded by post-intrusion faults which are not internally sheared. For instance, a hornblende-lamprophyre on the coast near Cairndoon strikes approximately parallel to the bedding, and is bounded on both sides by faults which shear the dyke marginally. The centre of the dyke shows no sign of shearing, and has a completely random orientation of hornblende phenocrysts.

3. ? Tertiary intrusive phase.

Five dykes of analcite dolerite have been recognised in the area (see Appendix, I p. 118 for description). Read (1926) concludes that these dykes are Tertiary in age on the grounds that a similar analcite dolerite cuts the New Red Sandstone near Stranraer. The average trend (N.W.-S.E.) of the dykes supports Read's conclusion, since this is perpendicular to a direction of Tertiary tension found throughout much of Southern Scotland. A number of other dykes are indicated on 1" sheets 2 and 4 (H.M. Geological Survey of Scotland) as ?Tertiary dolerites, but these rocks are in fact fine-grained dark lamprophyres.

A noteworthy feature is that one of the dolerite dykes, located 600 yards north of Port Allen (478411) has been cut by two shear planes. One of these, sub-parallel to the regional strike, bears horizontal slickensides but gives no indication of the displacement of the dyke, although an adjacent parallel fault does show sinistral displacement. The other, striking north-south and approximately vertical, has displaced the dyke 20 yards dextrally. This it would appear that there has been Tertiary wrench movement on both strike faults and what were originally primary sinistral faults, the latter being reactivated with a dextral sense.

Support for Tertiary wrench-displacement on the strike faults is forthcoming from a recent paper by Robson (in press) on the Acklington Dyke in Roxburghshire and Northumberland. This Miocene intrusion has been cut by a number of wrench faults striking 040 to 050, which have mostly displaced it with a sinistral sense. The present author has observed a sinistral shear belt with the same orientation cutting the Whin Sill at High Force in Teesdale, which must therefore be post-Permian in age.

TABLE I

Summary of Structural Synthesis.

	σ_1	Fold phase	Faults	Intrusions	Mineral-isation
Tertiary	090-270		Dextral reactn. of strike faults; sinistral reactn. of Primary dextrals		
	025-205	F_5	Sinistral reactn. of strike faults; dextral reactn. of Primary sinistrals		
				Analcite-dolerites	
Hercynian	135-315	F_4	Late thrusts		Calcite-dolomite-barytes-quartz.
Caledonian				Late Hb. lamprophyres	
	185-005	F_3	Sinistral reactn. of strike faults		
				Bi. lamprophyres Early Hb. lamprophyres	Quartz-calcite-dolomite
	145-325	F_2	Pry. wrench faults		
			Normal displacement on strike faults	Felsites	
	135-315	F_1	Early thrusts		

Oblique-slip reactivation of strike faults and primary wrench faults also occurred under some of the above stress conditions.

5. Structural Synthesis.

Having described the various phases of folding, faulting and intrusion, it is now possible to put forward a structural history of the area, together with a tentative analysis of the stress conditions responsible (Table 1).

It is usually assumed that strain structures (folds, faults, intrusions) bear a direct spatial relationship to the stresses which have produced them, although some authors have gone further than others in applying these assumptions to individual structures. Recent theoretical and field studies on similar folds suggest that more caution should be exercised in deducing stress conditions from these structures (eg. Flinn 1963, p.425; Ramsay 1960, pp. 88-89). The stress conditions responsible for the formation of faults and minor intrusions are if anything less well known.

In the Whithorn area, most F_1 fold axes show features of concentric and of similar folding (pp. 30-3). On theoretical grounds, it is considered likely that folding began concentrically, but later changed to a similar type of deformation, with the development of cleavage and chlorite grade regional metamorphism (p. 31). The similar folding thus accentuated pre-existing concentric folds which had been formed perpendicular to the main compression direction 135-315. The consistent orientation of a conjugate set of primary wrench faults throughout the area, and the trend of slickensides on thrusts also indicate a main compression at about 135-315. In view of this, it is likely that the same stress conditions were responsible for the formation of F_2 folds coaxial with F_1.

There is no doubt that all the various fault phases occurred later than the F_1 fold phase because they are frequently observed to cut or deform F_1 axes. The evidence of fault intersections shows that most of the thrusts were early structures (p. 43), and the association of low-angle thrusts with recumbent F_1 folds in part of the area suggests that thrusting occurred when F_1 folding had altered the rocks to an extent at which brittle fracture ensued. It has also been suggested (p. 43) that the present disposition of the thrust planes indicates a later tilting during the F_2 fold phase.

The age relations between strike faults and primary wrench faults are at first sight inconclusive, since they mutually displace each other in approximately equal ratios. However, it has been argued (pp. 38-40) that most of the strike faults have suffered at least two distinct movements: an early dip-slip and later strike-slips. The simplest explanation of the relations between the two groups of faults is that the wrench faults were formed between the early and late movements on the strike faults. This is confirmed by the fact that where strike faults displace primary wrenches, they do so with a strike-slip movement, mostly sinistral (see p. 39).

The next step in the argument concerns the nature of the dip-slip movement on the strike faults, which in two cases appears to be associated with F_2 folds. Thus a large F_2 monocline at Stein Head is adjacent and parallel to the Isle of Whithorn Fault (Plate 12A). This fault is a vertical feature formed by an initial dip-slip movement, deduced from exposures at The Barns (p. 39). Similarly, a horizontal antiform extending 400 yards south-west from Thief's Hole is adjacent and parallel to a vertical fault, which may also be seen in the cliff, beside the antiform. However, no other F_2 folds are coincident with strike faults, and it is thought unlikely that both sets of structures were formed together since the major strike faults downthrow to the south, while the major monoclines face northward. If it is true that dip-slip movements on strike faults did not occur during the F_2 compression, then the simplest explanation is that they took place during the release of compression between F_1 and F_2. The strike faults would thus have been normal fractures, which were followed by wrench faulting towards the end of F_2 compression. It should be stressed that various other interpretations are possible, but are more complex than the one suggested here. The irregular nature of the fault planes may indicate later folding, but the evidence is not sufficiently definite to be used as proof.

The placing of intrusive phases in this sequence is somewhat more problematic. The earliest set of dykes, the felsites, were probably intruded after the dip-slip movement on the strike faults. In some cases they exploit the pre-existing planes of strike faults, for example in a cave 130 yards north of the Gray Mare's Tail, and south of Port McGean (492485). Similar occurrences are described by Kelling (1961, p.69) from the Rhinns of Galloway. The small number of felsite dykes which trend approximately perpendicular to the strike are tentatively assigned to ac joints formed during the F_1 compression and filled in the subsequent tensional period, when the other felsites were intruded. Felsites perpendicular to the strike are somewhat darker than the others, and may have been intruded later (see Appendix I), but there is no structural evidence for this.

The evidence regarding the lamprophyres is somewhat contradictory. Both biotite - and hornblende - bearing types are displaced by primary wrench faults (sinistrals and dextrals), but also appear to fill similar fractures. This can be explained either by supposing two intrusive phases for both lamprophyric types, or alternatively two periods of wrench movement on the faults. Dextral fault planes have been filled by biotite - and hornblende-lamprophyres, whereas the latter are exclusive to sinistral fault planes (~~Figs~~. 23). Most of the hornblende - lamprophyres associated with sinistral faults occur in one locality, 300 yards east of Castle Feather, where the fault planes are thickly coated with barytes dolomite and calcite (with small amounts of chalcopyrite). The dykes are highly carbonated*, and although not internally sheared, they bear oblique and horizontal slickensides, as do many of the mineral veins. Such extreme carbonation does not occur in any other dykes, (including sheared ones) and can only be attributed to the metasomatic effect of fluids from the veins. The veins are therefore younger than the dykes - as would be expected, since similar mineralisation in the Leadhills - Wanlockhead area is Hercynian in age (pp. 120-1). Since the veins bear horizontal and oblique slickensides, there is clear evidence of strike- and oblique-slip reactivation of the faults after or during vein formation, and therefore subsequent to dyke intrusion. Additional evidence of later reactivation along primary wrench fractures has already been given (pp.44-5), and it seems reasonable to attribute the anomalous relations between wrench faults and lamprophyres to this effect. It is therefore assumed that most of the lamprophyres are younger than the primary wrench faults, and were intruded along these fractures (as well as strike faults) in the tensional period which followed the F_2 compression. There is, however, one example of a biotite - lamprophyre which suggests intrusion at the same time as a primary

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* A specimen investigated by x-ray diffraction gave an excellent calcite peak.

dextral fault was being formed (p. 50). Since wrench faults are formed under conditions of a horizontal maximum compression, this suggests that the magma must have been under considerable hydrostatic pressure. In view of the repeated movements along faults, the relative ages of the two types of lamprophyre are best based on their relation to F_3 folds, and to each other. As already suggested (p. 48) the F_3 phase of folding appears to follow the biotite-lamprophyre dykes and precede the later hornblende-lamprophyres. However, a poorly-represented early set of hornblende-lamprophyres must also be pre-F_3 in age, since they are older than the biotite-bearing types (p. 49).

Two main features resulted from F_1 and F_2 folding, and the various fault and intrusive phases described above. Firstly, since the dip of the beds had almost everywhere become very steep, further large-scale folding could only produce vertical or sub-vertical axes. Secondly, the wide distribution of various faults discouraged the formation of new primary fractures; further stresses resulted instead in the reactivation of existing faults, or shearing along dykes.

On the whole there is little evidence of concentric folding in the formation of F_3 axes (see p. 32), and there is certainly no association of conjugate primary shears. For these reasons, there are theoretical limitations to assuming a maximum stress direction at right angles to the modal axial plane for this fold system (p. 54). However, if a north-south compression during F_3 folding is assumed, such a stress would be very likely to initiate the sinistral slip observed on many of the strike faults. A lower limit to the age of F_3 folding is shown by a hornblende-lamprophyre which cuts F_3 folds at Shaddock Hole (p. 49). There is no reason to suggest that this intrusion is not a member of the Caledonian suite, and thus F_3 can be assigned to the Caledonian.

It is very likely that the calcite-dolomite-barytes mineralisation is Hercynian (sensu lato) in age (Temple 1956, Hobson 1959). According to Temple, the mineralisation at Leadhills accompanied sinistral shearing on approximately N - S fractures, for which the maximum stress would have been orientated at about N.W.-S.E. This stress could also have resulted in the formation of F_4 folds and their associated thrusts. It may be significant that these thrusts are frequently mineralised by quartz, and that quartz is the last mineral of the paragenetic sequence at Leadhills (Temple, 1956, pp. 97-99). These thrusts are demonstrably younger than F_3, since at Monreith Black Rocks F_3 axes are displaced by a thrust, while a biotite-lamprophyre dyke 200 yards north of the Gray Mare's Tail has been cut by a thrust. A post-Caledonian age therefore seems likely for the F_4 folds and thrusts, while the quartz mineralisation on the latter suggests a tentative Hercynian dating, somewhat later than the main barytes mineralisation.

The reasons for which F_4 folds are considered to be older than F_5 folds have already been given (pp.29-30). F_4 folds probably arose during a period of approximately N.W.-S.E. compression; their variation in size and style may be due to depth of burial: low-amplitude brittle folds at higher levels, and greater-amplitude flow folds at somewhat increased depths. The latter probably developed by transport of material perpendicular to <u>b</u> in a nearly horizontal direction, under stress conditions which also gave rise to thrusting. The irregular nature of the thrust planes may also be due to the relatively plastic condition of the rocks.

The best evidence bearing on the age of F_5 folding is given by the Tertiary dolerite dyke near Port Allen (p.53). This dyke has been sheared by a wrench fault with the same movement sense (dextral) and orientation (N-S) as the mode of the F_5 kink bands, and it is therefore suggested that the kink bands are contemporaneous with the shearing of the dyke.

Theoretical considerations suggest that kink bands only form in rocks with a pre-existing foliation, such as would be found in superficial layers of the earth's crust in the later stages of orogenesis. Apparently identical folds have been produced by Paterson and Weiss (1962) in experiments on phyllites and mica schists. Phyllites compressed parallel to their foliation developed conjugate sets of kink bands, while specimens compressed at 25° and 45° to the foliation developed single sets, the orientation of which is not given. This work suggests that the single set of kink bands in the Whithorn area arose from a compression somewhat oblique (in an anticlockwise direction) to the N.E.-S.W. foliation.

Such a compression would also be likely to reactivate the strike faults, especially the near-vertical ones, in a sinistral fashion. That this has taken place is indicated by the shearing of the Tertiary dyke near Port Allen by a strike fault bearing horizontal slickensides, and the existence of a parallel fault a few yards away, which shows a sinistral displacement. Thus it seems likely that dextral kink banding, dextral reactivation of N-S faults (originally primary sinistrals), and sinistral reactivation of strike faults all arose from an approximately NNE-SSW Tertiary compression.

The stress systems so far deduced are still inadequate to explain a small number of fault movements. These are strike faults with dextral displacement (12 examples), and faults approximating to the primary dextral mode at 120, but showing sinistral displacement (9 examples). Both of these could be explained by reactivation of the pre-existing shears by an approximately E-W compression. There is no evidence for the age of such movements, however.

A few examples have been noted of faults striking parallel to the modes of primary wrenches, but bearing steeply pitching slickensides, ~~(Fig.)~~. Most of these can be explained by oblique-slip reactivation of primary wrench faults under one or other of the stress systems discussed above.

6. Comparisons with Other Areas.

The areas with which structural comparisons will be made are shown in Fig.2, and will be discussed under the separate headings of folding, faulting and intrusions.

1. Folding.

There is general agreement on the stress conditions responsible for the Main Caledonian folding. The northward-facing monoclinal structure proposed by Craig and Walton (1959) is accepted by Kelling (1961), Warren (1962), Gordon (1962) and Anderson (1962), although the cross-sections given show that major folds other than monoclines are also present. The present work supports the major monoclinal structure.

The fact that the Main fold phase consists of two periods of folding has been recognised in the Girvan area by Williams (1959). The existence of the later period, which is called the Ardwell fold phase, is based on the variation in plunge of the Main fold axes observed on the Ardwell shore (Williams 1959, pp. 633-4). There appears to be no evidence of refolding of earlier folds, except that implied on p.635:

" The more extensive belts of inverted successions, have been further folded into antiforms and synforms,..."

Many inverted folds are due to drag along fault or thrust planes, but the remainder:

"...appear to be penecontemporary digitations of the major inverted folds and do not show any significant departure from the disposition of the latter".

These statements suggest that the later folds are in fact coaxial with the early folds of the Main phase, and are therefore closely analogous to the F_2 phase of the Whithorn area. The plunge variation of early fold axes on the Ardwell shore is probably due to deflection of the main compression by irregularities of the basement, as is suggested by Williams on p.643, rather than to refolding. The effect of the basement may be the partial explanation of the similar variation in plunge of F_1 folds in the Whithorn area.

A fold which closely resembles a typical F_2 fold of the Whithorn area is described by Anderson (1962, pp.181-2) from the Ards Peninsula, Co. Down. The fold is a broad open monocline parallel to the general trend of the Main folds, and has refolded an earlier cleavage. By analogy with the Whithorn examples, it is probably an F_2 fold which has refolded F_1 cleavage. Kelling (1961) has described three phases of folding from the Rhinns of Galloway, of which two are alleged to be Caledonian in age. However, Kelling's analysis has been strongly criticised by Anderson (1962, pp.228-9) on the grounds of insufficient data.

The style of deformation displayed by Main phase folds is discussed by Williams and Anderson. Concentric style predominates in the Girvan area (Williams 1959, p.631, p.634, whereas similar as well as concentric folding has been recognised in the Ards Peninsula (Anderson 1962, p.168). Anderson also stresses the control of style by lithology, in that similar folding only occurs in thin-bedded fine-grained rocks, while in other rock types concentric folding is displayed almost exclusively. Some folding by plastic flow has also taken place during similar folding, and is attributed to early folding of unconsolidated sediments (Anderson, p.178).

The style of folding in the Whithorn area resembles that of the Ards Peninsula more closely than that of Girvan, although it appears to be more intense in Whithorn than in the Ards. Evidence of similar folding during F_1, F_2 and F_3 is almost everywhere apparent, and is found in all lithologies, although it is much more marked in fine-grained beds (pp. 30-33). There is usually strong evidence of concentric folding as well, and it is thought that deformation commenced by the latter mechanism. Measurements of bed thicknesses around fold axes (pp. 32-33) suggest that some plastic flow accompanied similar folding. The recrystallisation of chlorite without mobilisation of quartz, in the matrices of greywackes as well as in argillaceous rocks, suggests a low grade regional metamorphism reaching a temperature and pressure of about 200°C and 2000 atmospheres respectively (Fyffe, Turner and Verhoogen, 1958, p.173). It therefore seems reasonable to suggest that plastic flow has been largely due to metamorphic conditions, as well as folding of unconsolidated sediments, and is a further indication of the greater intensity of deformation in the Whithorn area, as opposed to the Ards Peninsula.

Steeply plunging folds have been observed in mahy parts of the Southern Uplands, and various explanations have been put forward. Thus Walton (1961, p.75) has attributed steep folds in Kirkcudbrightshire to transcurrent movement along the strike, concentrated into zones of intense deformation. Anderson (1962, p.182) describes similar folds in the Ards Peninsula, and tentatively equates them with Walton's examples. The similarity between the folds in Kirkcudbright and F_3 folds of the Whithorn area is very marked, and there is every reason for believing them identical in age and origin.

Steeply-plunging fold axes have also been observed in Berwickshire (Dearman, Shiells and Larwood, 1962). These authors suggest that the steep axes were formed by refolding of sub-horizontal Main fold axes by later folds with shallow axial planes. The relation between the two sets of axes is expressed as follows (p.275):

"... it can be demonstrated that folds with a north-east to south-west axial trend have been refolded about north-west to south-east axes, and that the two fold directions share a common axial plane".

The apparent contradiction in this statement is presumably intended to refer to the N.E-S.W. axial plane (A_1 in Fig.2, p.276) before and after refolding by A_2. It is evident from the text that axes corresponding to A_2 have not been found in the field, since they are nowhere described.

The similarities in style and orientation of folds seen on the Wigtownshire and Berwickshire coasts suggest that the sequence of folding has been basically the same. The Wigtownshire evidence shows that the folds termed F_3 were originally formed with steep plunges, and have not attained this state by a process of refolding.

The rapid and extreme variations of fold axes described and illustrated by Dearman _et al_ (1962) must indeed be due to refolding. However, it has already been suggested in this thesis (pp. 28-9) that the refolding is of already-vertical F_3 axes, and is largely achieved by F_4 axes, with low-angle axial planes. Part of the variability of the plunge may, however, be due to initial variations in F_3.

In discussing structures exposed at St. John's Roads (pp. 279-281), Dearman _et al_ (1962) suggest that the variably plunging antiforms and synforms there exposed may be explained by refolding, on the same basis as the uninverted folds elsewhere (pp.281-2). This implies that the inverted folds were formed in one fold phase, but the present author would dispute the possibility of such folds arising in any single fold movement. The Wigtownshire examples suggest that sub-horizontal antiforms and synforms arose by the F_2 refolding of the inverted limb of an F_1 fold (pp. 18, 21-2); subsequent F_4 refolding has given rise to the variable plunge.

Folds which appear to be analogous with F_4 folds of the Whithorn area have been observed in the Ards Peninsula by Anderson. They are described as kink bands with shallow-dipping axial planes (Anderson, p.198), and are distinguished from structures termed second-folds by a lack of strain-slip cleavage, which the latter possess. Second-folds are illustrated in Anderson's Plates 128-131, and closely resemble larger examples of F_4 folds from the Whithorn area. Lineations produced by intersection of second-fold cleavage with the early cleavage are also similar to F_4 lineations seen in Whithorn. The main difference between second-folds and low-angle kink bands of the Ards Peninsula seems to be one of scale, and it is here suggested that they are analogous to the varied types of F_4 folds formed at different depths in the Whithorn area.

The F_5 folds of the Whithorn area also have direct analogues in the Ards Peninsula, which have been called kink bands by Anderson. They differ in that the Ards structures form a conjugate set with both sinistral and dextral kink bands represented. The Whithorn folds are solely dextral, and have an orientation which is the same as the dextral set of the Ards Peninsula. The Whithorn kink bands are also smaller in amplitude, and are not bounded by such well-defined shear planes as those described by Anderson.

Structures equivalent to F_5 are also found in the Girvan area (Williams 1959, p.650), and have been termed cross-folds. The account given suggests that two periods of shearing and attendant cross-folding are being described, one resulting from maximum pressure north-west to south-east, and the other due to maximum pressure at right angles to this. Cross-folds described elsewhere (Williams, 1959, p.634, p.664) correspond to the latter system and appear to be equivalent to F_5 folds of the Whithorn area, and the vertical kink bands of the Ards Peninsula. These cross-folds are said to be older than the Main wrench phase in the Girvan area. In view of the postulated change in maximum stress direction from N.W.-S.E. for the Main fold phase, through 90° for the cross-folds, and then back again for the Main wrench phase, it is surprising that supporting evidence for this sequence of events is not given.

The cross-folds (F_5) of the Whithorn area are considered to be much younger, since they have folded lamprophyre dykes and also a horizontally-slickensided surface formed by lateral movement on the Isle of Whithorn Fault (p. 39). The evidence on which the age of F_5 kink bands is based in the Ards Peninsula rests largely on the recognition of two intrusive phases, and will therefore be considered after the intrusions have been discussed.

2. Faulting.

Craig and Walton (1959) postulated major N.E.-S.W. strike faults to explain the structure of the Southern Uplands; such features have been recognised by Anderson (1962), Kelling (1961), Gordon (1962) and Warren (1963). The present work underlines the importance of major strike faults, and puts forward an interpretation based on analogy with similar minor structures. Both major and minor strike faults are thought to have moved initially with a predominantly dip-slip movement during the Main fold phase, and to have been subsequently reactivated by essentially strike-slip movements (pp. 39-40). This interpretation differs considerably from that put forward for similar N.E.-S.W. faults in the Girvan area* (Williams 1959; conclusions summarised pp. 664-6). Williams' interpretation may be briefly stated as follows. The faults are post-Caledonian, comprise three normal phases, and indicate a major change in stress conditions with respect to earlier phases, in that the maximum principal stress (σ_1) had become nearly vertical for the first time (Williams Fig.14, p.663). The detailed account of these faults is given under the heading of Oblique-slip Faults (pp.650-659). In the

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* In the Girvan area the major N.E.-S.W. faults tend to be somewhat oblique to the regional strike, but this is not considered to be of fundamental importance.

first paragraph of this account it is stated that these faults bear striations (slickensides) pitching at any angle between 0° and 30°. In the rest of the section, only two shears bearing slickensides pitching more steeply than 30° are mentioned - one is 35° and the other is 65° (p.657). It must therefore be assumed that these are exceptions to the opening generalisation, and that in fact most of these faults suffered predominantly strike-slip displacement. They cannot, therefore, be termed "normal" faults under any circumstances, although the earlier use of the term "wrench-normal hybrid" is quite legitimate.

In the light of the above discussion it seems reasonable to suggest that the evidence concerning strike faults is very similar in the Girvan and Whithorn areas. Thus the occasional strike faults bearing steeply-pitching slickensides at Girvan are probably equivalent to the early dip-slip movement recognised in the Whithorn area. Similarly, the almost universal post-Caledonian oblique strike-slip on these faults can probably be correlated with the later strike-slip movements observed around Whithorn. As indicated by Williams (p.666) there is evidence that these faults underwent several phases of movement. The present work has shown Tertiary wrench movements on strike faults (p. 53), as well as possible Hercynian (p. 58) and late Caledonian (p. 60) wrench displacements. An important factor in the Girvan area is that the presence of rocks of different ages and lithologies gives considerable evidence on the amounts of fault displacement. It is probable that most of the post-Caledonian displacements on strike faults can be explained in terms of oblique - but predominantly strike-slip. The contention that there was a major post-Caledonian change to a stress field in which σ_1 became vertical must therefore be viewed with doubt.

Major strike faults are important features of the structure of the Ards Peninsula (termed block faults by Anderson, 1962). They appear to be very similar to those of the Whithorn area, as the following data indicate. The Doctor's Bay Fault (Anderson, 1962, p.33) shows evidence of two movements, vertical and horizontal (sinistral), while the Orlock Bridge Fault (pp.25-6, 37) similarly indicates near-horizontal as well as dip-slip movement. An early age for these faults is suggested by the displacement of the Tieveshilly and Coalpit Bay Faults by primary sinistral wrenches (p.39). At Millin Bay a minor strike fault is displaced by a sinistral wrench fault (p.36).

Other evidence of more than one movement on a major strike fault (the Southern Uplands Fault) has been observed by Kelling (1961) in the Rhinns of Galloway. A southerly downthrow of 3000-4000 feet is deduced from stratigraphical evidence and the feature is interpreted as a normal fault (p.66). However, the occurrence of nearly horizontal slickensides on shears associated with the major fault implies a later strike-slip movement. Walton (personal communication) has found similar evidence of strike-slip movement on the Southern Uplands Fault in Glen App, although stratigraphical evidence again suggests considerable earlier dip-slip throw. Similarly, Jennings (1961, pp.47-8) deduces that the Kerse Loch Fault (parallel to and roughly 5 miles north of the Southern Uplands Fault) has been through at least one period of dextral wrench movement.

The relation between primary wrench faults and the Main fold movement has been confirmed by all the authors, although the direction of maximum principal stress differs somewhat. Williams attributes the spread of wrench faults in the Girvan area to second and third order shears developing as a consequence of changed stress conditions after the formation of primary wrenches. Anderson, on the other hand, attributes the wide spread observed in the Ards Peninsula to a Gaussian distribution about the modal values. The results from the present area show a similar spread, which may include second and third order faults, but since there are no obvious secondary peaks in the distributions (Fig. 19), this is unlikely. The distribution of dextrals is rather strange in having a very broad peak about an average of 110, while the sinistral peak is sharp at about 005.

The age deduced for the early thrusts in the Whithorn area is the same as that suggested for the Girvan area by Williams (ie. at the end of earliest Main fold movements - F_1). The only difference lies in the scale of the dislocations, which are very considerable in the Girvan area (Williams 1959, pp.636-644), but of minor importance around Whithorn. Structures equivalent to the late thrusts of the Whithorn area do not appear to have been recognised elsewhere.

3. Intrusions.

Previous work on the Caledonian dykes in the area around Whithorn has been largely concerned with petrography (Read, 1926). For regional comparisons of their structural significance it is necessary to turn to the studies of Reynolds (1931) and Anderson (1962) in the Ards Peninsula, Co. Down, and Blyth (1949) in Kirkcudbrightshire.

Reynolds distinguishes two main periods of lamprophyre intrusion on the grounds that one series has been crushed, whereas another series is unaffected. The Older Series are said to be largely pyroxene minettes, while the Younger Series are divisible into two groups of lamprophyres, respectively bearing hornblende and biotite/pyroxene, of which the latter are younger. The mechanism of crushing of the Older Series is briefly discussed (Reynolds 1931, p.98), and they are distinguished from the Younger Series on rather loose petrological grounds (p.103): "Speaking generally, the proportion of felspar to ferro-magnesian minerals is higher in these rocks than in the Younger Series".

There is no quantitative data to illustrate this statement, which is in any case based on the recognition of ferromagnesian minerals in the form of quartz - carbonate pseudomorphs (with the rare exception of biotite - Reynolds p.102). Since these rocks are in addition foliated, it is evident that any petrological classification based on such criteria is highly dubious. In fact little is made of the crushed dykes, and it is obvious that the classification and petrogenesis of the unaltered Younger Series was Reynolds' main interest. Anderson, however, claims a more definite distinction between the two series of dykes (Anderson 1962, pp. 147-8):

" A real difference in petrology, as established by Reynolds, makes it unnecessary to rely on these rather vague field distinctions".

By "vague field distinctions", Anderson refers to the fact that not all Older Series dykes are crushed, nor is the reverse condition fulfilled, (Anderson 1962, p.147):

" There are crushed members of the Younger Series, particularly on the west coast, and relatively uncrushed Older Series dykes south of Slanes Point, although the generalisation that the Younger Series are "noticeably different, being fresher and more massive, and showing no signs of crush" (Reynolds p.98) is largely true...".

In the absence of quantitative data on their composition, it is suggested that the Older Series of the Ards Peninsula may be equivalent to the felsites of Wigtownshire. These are thought to be the earliest intrusions of the Whithorn area (pp. 47-8) but comprise unsheared as well as sheared members. Because of this, shearing parallel to the dyke walls, as suggested by Blyth (1949) for dykes in Kirkcudbrightshire, is preferred to the crushing perpendicular to the walls invoked by Reynolds, since the latter mechanism should affect all dykes present.

Blyth (1949) suggests that the Kirkcudbrightshire dykes (mostly parallel to the regional strike) filled fractures which arose by dextral shearing, and that the shearing of the dykes has resulted from further dextral wrench movements along the strike. He suggests that the relaxation of compression after the Main fold phase would have been insufficient to produce a tension, but in this he neglects the effect of hydrostatic pressure of the dyke magma, which could easily be sufficient to make up for tensional deficiencies. In any case, the stress conditions which would produce strike-slip shearing are even less condusive to dyke formation.

In the Whithorn area, the evidence suggests that at least some of the shearing took place after consolidation (for instance the hornblende-lamprophyre at Cairndoon, see p. 52). On the other hand, there is one case (p. 50) in which strike slip movement occurred along the fault fissure while it was being filled with dyke magma. The general conclusion is that shearing parallel to the dyke walls took place before, after, and perhaps during dyke consolidation. It is considered that most of the dykes were originally formed as tensional features, or rather as features formed perpendicular to a direction of minimum compression (see pp. 50-1). These remarks are applicable to dykes parallel to primary dextral and sinistral wrenches as well as strike faults, and to lamprophyres as well as felsites. It should also be noted that in Kirkcudbrightshire the evidence points to dextral movement on strike faults, whereas the majority of observed strike-slips are sinistral in the Whithorn area.

In the Ards Peninsula two groups are recognised within the Younger Series (uncrushed) dykes, of which hornblende-lamprophyres are earlier than biotite/pyroxene-lamprophyres (Reynolds 1931). In the area around Whithorn, evidence already given (pp. 48-9) indicates that there was some overlap in the intrusion of these two groups, and it is suggested that there were two periods of hornblende-lamprophyre intrusion.

Much of the relative dating of faults and later folds in the Ards Peninsula is based on the relation these structures bear to the Older and Younger dyke Series. Thus it is said that the kink bands (equi?valent to F_5 folds of the Whithorn area) are later than the Older Series dykes, but pre-date a set of wrench faults and the Younger Series dykes (Anderson 1962, p.196). However, as regards the kink bands this is quite contradictory to the evidence observed in the Whithorn area, where several examples of dykes which closely resemble the Younger Series are affected by F_5 kink bands. These dykes are usually massive, in which case the kink bands traverse them as a series of sinuous *en echelon* gashes ~~(Plate)~~, but a few thinner members are affected by kink bands in the same way as the surrounding sediments (Plate IIB). It is therefore suggested that the massive nature of the Younger Series dykes and their lack of foliation are largely responsible for their frequent resistance to the formation of kink bands. The observation that dykes and kink bands are cut by later wrench faults in the Ards Peninsula does not conflict with the evidence from the Whithorn area, for which late reactivation of wrench faults has already been described (p. 72).

4. Conclusions.

It is apparent from the above discussions that there is a remarkable similarity in the structures observed in the Whithorn area and the Ards Peninsula. Preliminary studies in Berwickshire suggest that more detailed work would reveal structures with a similar correspondence, thus linking the Silurian rocks over considerable distances. The structural resemblances to the Ordovician rocks of the Rhinns of Galloway and the varied rocks of the Girvan area are not so strong, however. This is probably due to the somewhat different response of rocks of different lithologies and at different levels to what were essentially the same stress conditions.

SEDIMENTOLOGY

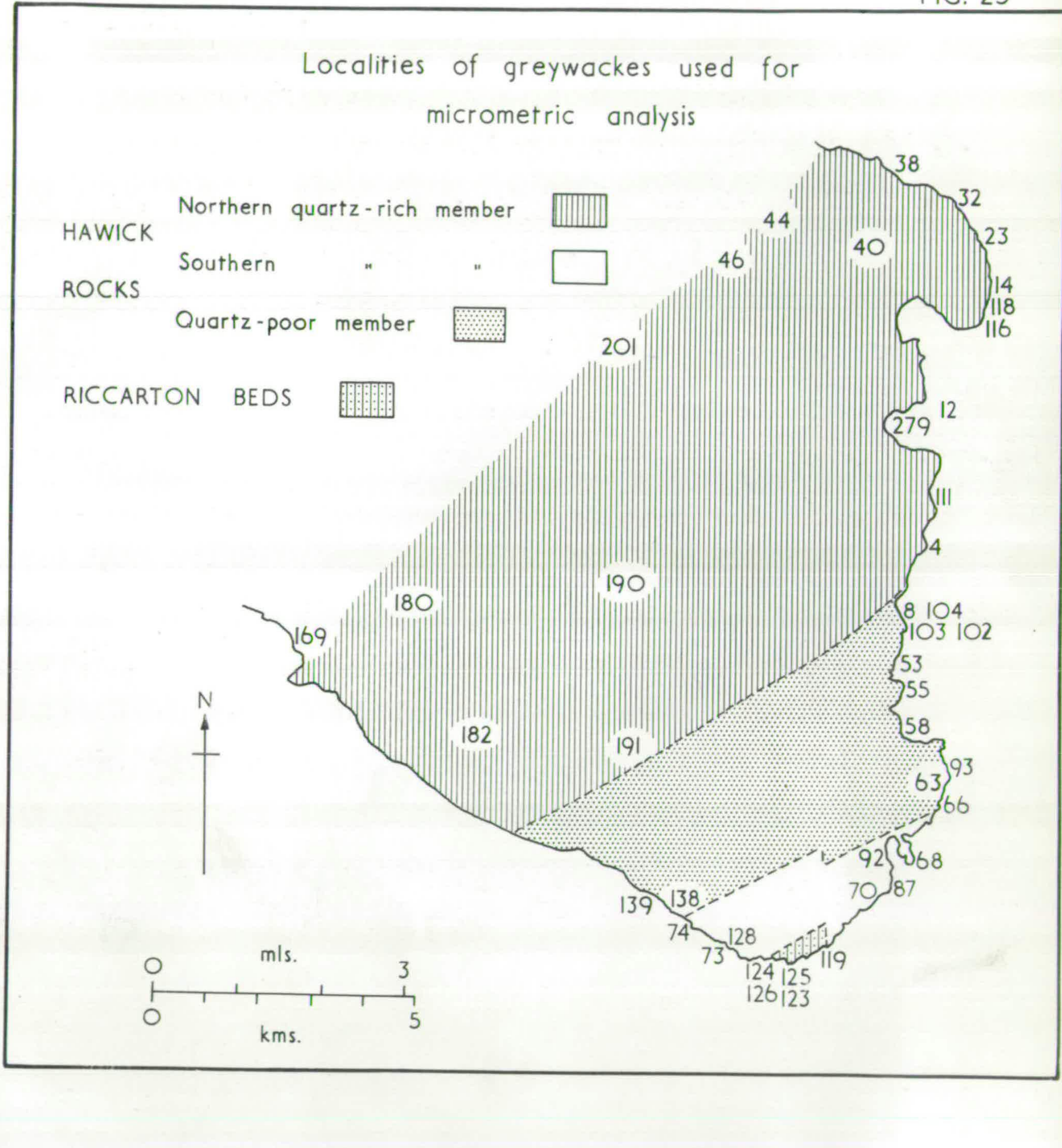
1. Introduction.

Compared with other parts of the Southern Uplands in which sedimentological investigations have been carried out (e.g. Walton 1955, 1956, Kelling 1962, Gordon 1962), the Whithorn area suffers from a number of disadvantages. Firstly, coarse-grained sediments are comparatively rare, and never attain the conglomeratic proportions described from other areas. Secondly, they are frequently affected by diagenesis, so that in many cases the original constituents of the rocks cannot be reliably determined. Thirdly, although large numbers of excellent current structures can be observed, the tectonic complexity of the area introduces considerable difficulties into the deduction of palaeocurrent directions.

For these reasons, and because of the recent work of other authors, sedimentary petrology and palaeogeographic reconstructions will not receive detailed treatment here. Additional attention will however be paid to the fine-grained sediments, and to the diagenesis of the coarse-grained rocks.

2.

FIG. 25



Localities of greywackes used for
micrometric analysis
HAWICK
ROCKS
Northern quartz-rich member
Southern " "
Quartz-poor member
RICCARTON BEDS
N
mls.
O
3
O
5
kms.
38
32
23
14
118
116
44
40
46
201
12
279
111
4
190
180
169
8 104
103 102
53
55
58
182
191
93
63
66
92
68
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123

2. <u>The coarse-grained sediments</u>.

The coarse-grained sediments of the area are termed greywackes because they show most of the characteristics generally included in a definition of these rocks (Pettijohn, 1957, pp.301-316). The typical greywacke features which are most frequently lacking are variety of clastic types, and "ideal" graded bedding (Kuenen 1953, Walton 1956).

The amount of sampling was determined only by the availability of fresh coarse-grained greywackes. Of these, the relatively unaltered specimens were subjected to micrometric analysis to determine the proportions of the different components present. The results of the analyses are given in Appendix II (pp.122-7). The components of the greywackes have been grouped under general headings, namely quartz, felspar, acid igneous, basic igneous, sedimentary and metamorphic fragments, and matrix. Nevertheless, even such a simple scheme is open to numerous errors of identification, which are well discussed by Jennings (1961, pp.138-9).

Quartz.

The most useful criterion for distinguishing different groups of Whithorn greywackes in thin section is the percentage of quartz fragments, because of the minimum operator variance involved in identifying quartz, and estimating its amount. This conclusion was tested by doing micrometric analyses for a number of greywackes from the Garheugh Formation (Gordon 1962). In each case the quartz percentages obtained were similar to those given by Gordon, but the figures for other components showed considerable differences.

Felspar.

The felspar present is mostly acidic in composition - orthoclase, albite or oligoclase, with rarer microcline and andesine - and almost invariably shows alteration to clay minerals and partial replacement by carbonates, (Plate 23B).

Acid igneous fragments.

The coarse-grained acid igneous fragments (granites, granophyres and granodiorites) are easily recognised, but are not very common because of the fine-grained nature of the greywackes. The disintegration of the coarse acid fragments has probably been the source of much of the quartz and felspar present, and also the occasional tourmalines and zircons.

Fine-grained acid igneous fragments are frequently indistinguishable from fine siliceous sedimentary fragments (cherts), (MacGregor and Eckford 1946). In some cases, however, the acid fragments can be recognised by the presence of minute felspar laths, and are probably felsites or rhyolites. A few somewhat coarser fragments show a trachytic texture of felspar laths, and may be trachytes or keratophyres, but they cannot be identified precisely.

Basic igneous fragments.

Basic igneous fragments of all grain-sizes are common, and usually exhibit a variety of textures which have been described as spilitic (Kelling 1962). However, the felspars are almost invariably oligoclase, as opposed to albite, which is the felsic constituent of true spilites (Dewey and Flett 1911, Battey 1956). Provided this fact is recognised, the term spilite is a useful one to describe an easily recognised rock type. Dolerite and gabbro fragments are not found in the Whithorn greywackes, but basalt fragments (indistinguishable from fine-grained spilites) may be present. Basic fragments which are common in sediments from other parts of the Southern Uplands but are noticeably absent from the Whithorn greywackes are andesites, hornblende and augite.

Sedimentary fragments.

Coarse sedimentary fragments include greywackes, sandstones (distinguished from quartzites by a lack of foliation) and occasional limestones, (which can be only dubiously distinguished from secondary carbonate). Fine-grained sediments include shales, siltstones and cherts. Shales and siltstones are common; some may have been derived as soft flakes from the underlying beds at the time of sedimentation. It is not always possible to distinguish shales from low-grade metamorphic fragments.

Metamorphic fragments.

Fragments of metamorphic rocks are not common in the Whithorn greywackes. The types found are quartzites, phyllites and schists. Garnet is the only metamorphic mineral which has been observed, and this is very rare.

Red micas.

Red micas have been found only in the greywackes and coarser siltstones of the Hawick Rocks, and since they are easily recognisable in hand specimen, they serve as a useful stratigraphical indicator. In thin section they show the optical properties of muscovite, and under high power magnification may show coatings of a fine red material, which is thought to be hematite (Plate 22A).

Matrix.

The matrix of the greywackes consists mostly of small fragments of the major constituents, and must therefore be arbitrarily defined as all material below 0.01 mm in diameter. X-ray diffraction of crushed material from greywacke matrices produced reasonable peaks for the clay minerals kaolinite and illite, and it must therefore be assumed that appreciable amounts of clay - grade material are also present (see p. 89).

3. The fine-grained sediments.

The fine-grained sediments of the area consist of shales mudstones and siltstones. These terms are not of themselves important since the presence or absence of visible fragments and/or lamination are largely independent of sediment type, whereas colour is an important and comparatively invariable criterion. Thus three types may be defined: green beds (mudstones and siltstones), red beds (mostly siltstones) and dark grey beds (shales and laminated siltstones).

a) Green beds.

Argillaceous sediments varying from khaki to grey shades of green are found throughout the area. They occur in two forms; as the fine-grained upper parts of greywacke units, and as independent units interbedded with the greywackes. The latter type of green bed usually lacks depositional structures and is predominantly of the mudstone grade. The green beds which form the tops of greywacke units are, on the other hand, frequently current-bedded, and contain much silt-grade material. The coarser grains are concentrated in the foreset laminae, in which weathering often reveals a preferential concentration of carbonates, probably introduced diagenetically (pp. 107-8).

The difference between the two types of green bed is thought to be solely due to the influence of the currents remaining after the deposition of the greywackes, which induced current-bedding and retained coarser material in suspension.

b) Red beds.

Primary red sediments occur solely within the Carghidown beds of the Hawick Rocks, which they characterise. They lack any form of depositional structure and vary in thickness from 1/8" to 20 ft. (the latter figure is somewhat uncertain due to probable distortion by folding). The red beds are mostly siltstones, since clastic grains (chiefly quartz) are readily visible, but there is a gradation into mudstones. They may occur interbedded with green beds (of the type which are not associated with greywackes); sometimes on a very fine scale. The contacts between red and green beds may be sharp or gradational; if the latter is the case, the colour changes through shades of purple between the red and green extremes.

The substance responsible for the red colouration is presumably hematite, which is the predominant pigment of almost all red beds (Van Houten, in press). However, it is not easily detected by the x-ray method used, because of a background radiation due to iron.

c) Dark grey beds.

Beds of this colour occur in the Riccarton Beds and in the Hawick Rocks (Kirkmaiden beds), but are not identical in all respects. Their common features are colour, weathering (to a rusty brown colour), sharp contacts with other sediments, and the fact that they are graptolitic. Graptolites have not been found in all the bands of this lithology, but it is assumed that this is merely due to lack of sampling.

The graptolitic bands of the Riccarton Beds are very numerous and reach thicknesses of several feet. They are mostly siltstone, containing appreciable amounts of quartz, and show a fine but irregular lamination consisting of discontinuous interweaving lenses of silt-grade quartz fragments, which resemble minute ripples. The irregular nature of the structure suggests that it is not of current origin; it may have resulted from a patchy quartz deposition accentuated by differential compaction of the argillaceous and carbonaceous material. By contrast, the graptolitic bands of the Hawick Rocks are thin and infrequent: nine bands, each less than one inch in thickness have been encountered in a rock sequence of several thousand feet. The beds are shales, their only sedimentary structure being a fine regular lamination.

d) Chemistry of the fine-grained sediments.

Two specimens each of red, green and graptolitic fine-grained sediments have been partially analysed (see Table II), but the results are unfortunately inconclusive. There is a clear differentiation between the TiO_2 contents of the three types, and the green beds contain notably more Al_2O_3 and MgO than the other types. The higher Al_2O_3 content of the green beds may be due to the higher proportion of kaolinite, but if this is so the MgO content should be lower, which is not the case. The higher manganese content of the red beds reflects the presence of MnO_2

TABLE II

Partial analyses of fine-grained sediments.*

	Red beds		Graptolitic beds		Green beds	
Sample no.	85	89	283	71	177	133
TiO_2	0.85	0.86	0.92	0.94	1.01	1.03
Al_2O_3	14.44	14.68	14.40	15.33	17.19	17.01
Fe_2O_3	9.68	6.54	5.65	5.85	8.43	8.60
MnO	0.072	0.172	0.044	0.040	0.039	0.046
MgO	3.24	3.42	3.30	3.42	5.90	5.73
CaO	2.26	1.31	2.49	2.32	1.80	1.12
K_2O	3.54	3.49	3.22	3.22	3.62	3.77
CO_2	2.06	1.66	3.28	1.80	1.43	1.23
C	0.23	0.06	0.35	0.28	0.02	0.14
S	-	-	0.75	-	-	-

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* Analysed in the Geochemical Laboratory, Grant Institute of Geology.

as arborescent growths and nodules. The approximate equivalence of iron content in red and green beds has been observed in other sedimentary suites (eg. Van Houten, in press, p.5), and is probably due to the presence of iron as silicate in the green beds. Fe''' silicate

An unexpected result is the comparatively high carbon content of one of the red beds (85), which is of the same order of carbon content as the dark grey graptolitic beds (see Table II). It is generally assumed that the preservation of red pigment requires oxidising conditions, which would not be maintained in the presence of free carbon. The results for sulphur are also surprising in that one of the graptolitic shales (283) contains an appreciable amount, but the other graptolitic shale completely lacks sulphur, as do all the other sediments analysed.

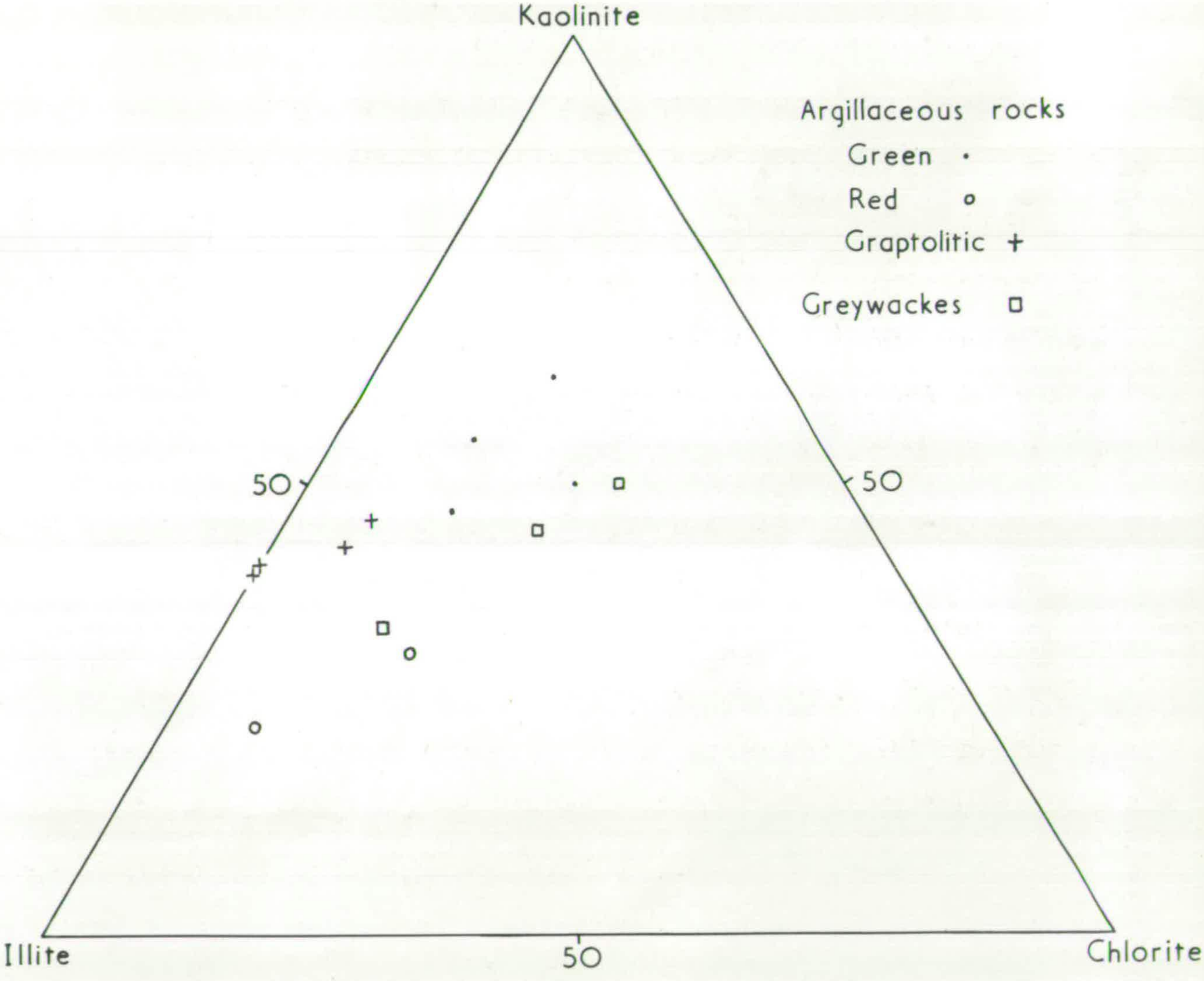
Warren (1962, p.204) quotes 0.5% organic carbon for a graptolitic shale from the Riccarton Beds south of Hawick and 0.95% sulphur as an average from three such beds. These results are of the same order as those obtained from the Whithorn graptolitic sediments, but are, as Warren points out, much lower than those obtained elsewhere (Bulman, 1955).

4. Clay Mineralogy.

The clay mineralogy of the fine-grained sediments and XRD greywacke matrices has been investigated by x-ray diffraction of

FIG. 26

Clay Mineralogy



clay samples, orientated by sedimentation onto porous porcelain tiles under reduced pressure. The results obtained show that illite and kaolinite are the principal clay minerals of these sediments; chlorite is an additional minor constituent (Fig. 26).

A few remarks may be made concerning the relation between sediment type and the clay minerals present, but conclusions must remain tentative on account of the inaccuracies of the methods and the small number of samples. Thus the fine-grained green beds are somewhat richer in kaolinite and poorer in illite than the red beds, whereas the graptolitic beds are intermediate in this respect. The comparative lack of kaolinite in the red beds does not necessarily imply that they were not derived from lateritic soils. Van Houten (in press) states that illite, chlorite and related clay minerals may prevail in the lower part of some red soils under conditions of incomplete weathering. He also points out that illite is commonly the dominant clay mineral in the terra rossa of the Mediterranean area. Grim (1953, p.357) suggests that the comparative rarity of kaolinite in pre-Devonian sediments may be due to metamorphic processes and the adsorption of alkalis to form micas.

Compared with the argillaceous sediments, the matrices of the greywackes are more variable in clay composition. They contain higher proportions of chlorite, a factor which may be partly due to the development of diagenetic and/or metamorphic chlorite (pp. 111, 31).

5. Sedimentary Structures.

Craig and Walton (1962) have described sedimentary structures from the Hawick and Riccarton rocks of Kirkcudbrightshire. The sedimentary structures of the Whithorn area are very similar, and it is therefore unnecessary to do more than list the types of structure present, and describe certain outstanding examples in more detail.

a) Bedding plane structures.

Flute marks, longitudinal ridge marks (Craig and Walton, 1962) and combinations of the two are the commonest greywacke sole markings around Whithorn, and are usually preserved in the form of moulds. Flute moulds vary in size from a foot to less than an inch in length, and also vary in other dimensions, in the amount of loading, in type, shape, and frequency on the bedding plane. Two localities deserve special mention. At Palmallet Point upwards of ten successive beds show under-surfaces completely covered with flute moulds (Plate 14A). The size of flute on each bed is remarkably consistent, although it varies from bed to bed. A consistent current direction (towards the north-east) is displayed throughout the whole exposure, as well as a consistent ~~assymetrical~~ asymmetrical loading trend. Prentice (1960) suggests that loading is partly due to horizontal flow of material due to the original current flow, or to settling of the deposits on a sloping surface.

PLATE 14.

Flute moulds at Palmallet Point.

A. General view of a typical under-surface.

B. Cross-section, showing internal laminations in the flute moulds.

A

B

PLATE 15.

A. Flute moulds, Isle of Whithorn. Some show corkscrew form, while terracing can also be seen (top left).

B. Groove moulds, Burrow Head.

A

B

PLATE 16.

A. Transverse ripples, Cairndoon.

B. Loaded transverse ripples, Palmallet Point.
The shale between the ripples fills sharp downward-facing depressions which resemble flame structures, except that they are inverted (Fig.24,B).

A

B

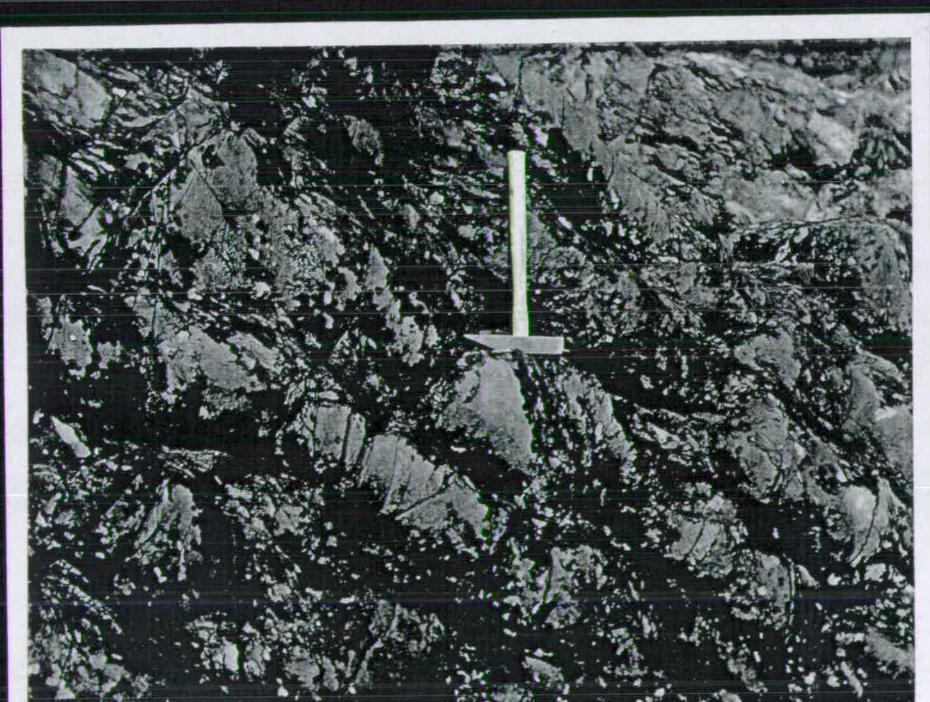


PLATE 17.

A. Section of loaded transverse ripple from Palmallet Point showing extreme distortion of laminae, due to loading.

B. Interference ripples, Castle Feather.

A

X 2

B

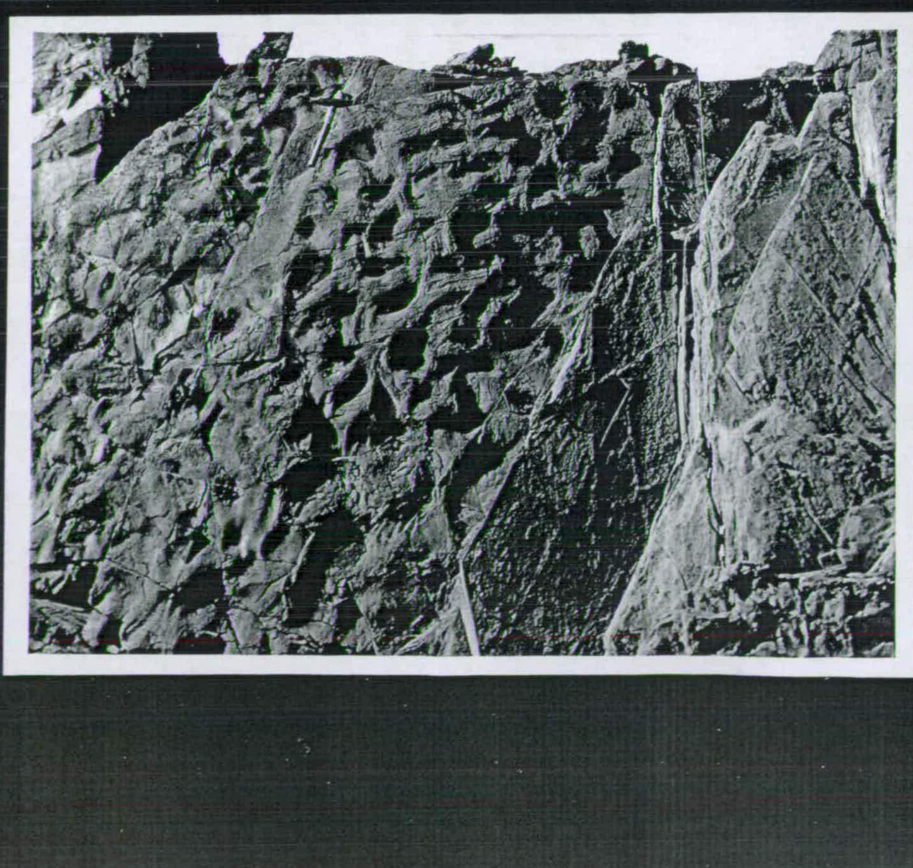
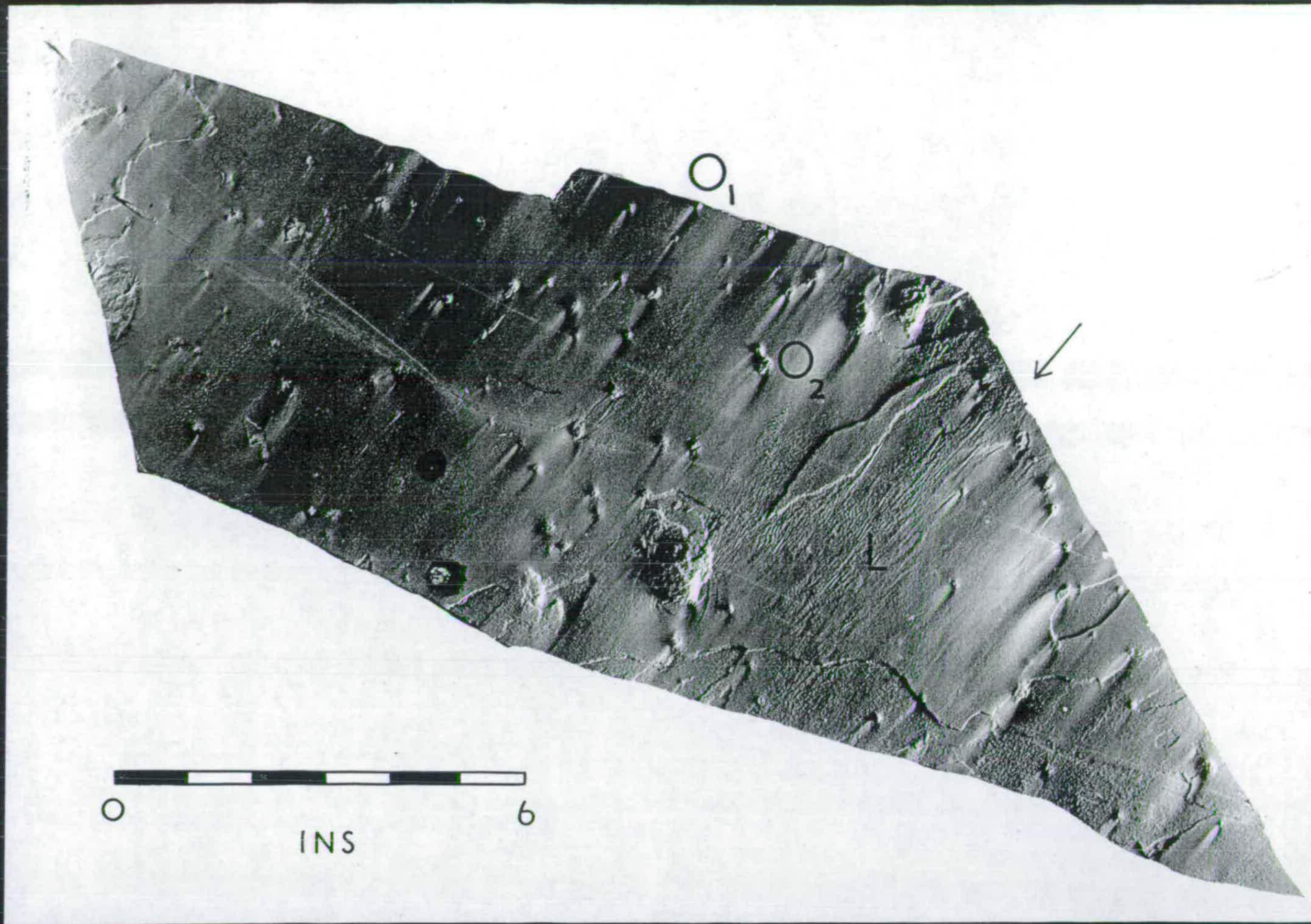


PLATE 18.

A. Longitudinal ridges (L) and obstacle scours indicate the same current direction (arrow shows trend). Scours caused by small obstacles have single 'tails' (O_1), whereas scars formed by larger obstacles have the double tails (O_2) characteristic of crescent marks.

B. Longitudinal section through a sand volcano, showing a central vent (V) which emerges at the top to form a crater (C).

A



B

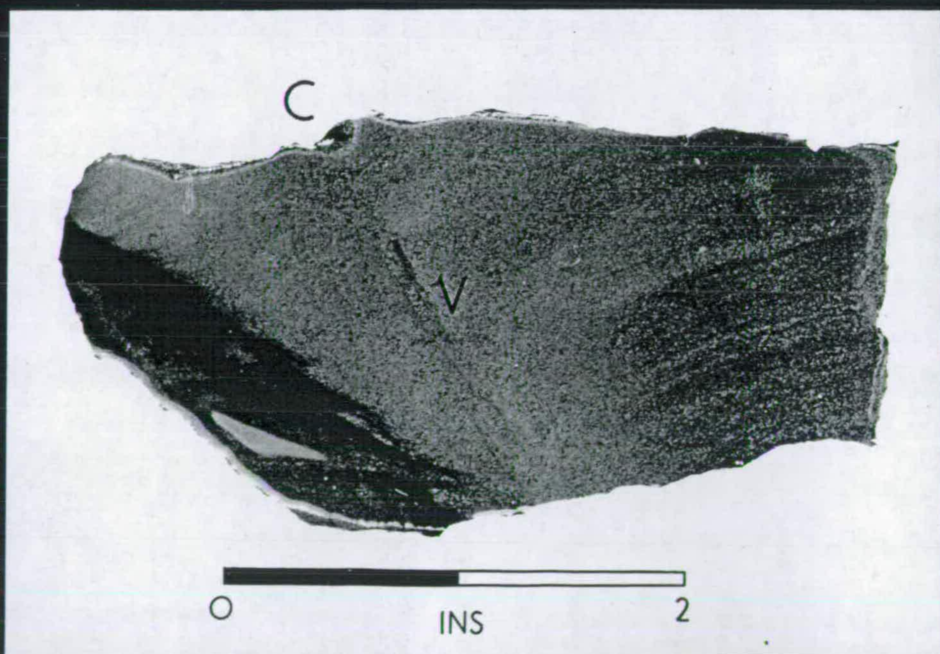


PLATE 19.

Sand volcanoes.

A. Cones with well-developed craters, and a few satellite conelets (The Barns).

B. Numerous satellite conelets. One of the main cones (centre, right) shows external slumping. (North of Port Allen).

A

B

PLATE 20.

A. Pseudonodules. The structures have been truncated at the top by the base of the succeeding bed.

B. Current bedding from the top of a greywacke unit. Coarser material has been deposited along the foreset laminae, which are more easily weathered on this account.

A

B

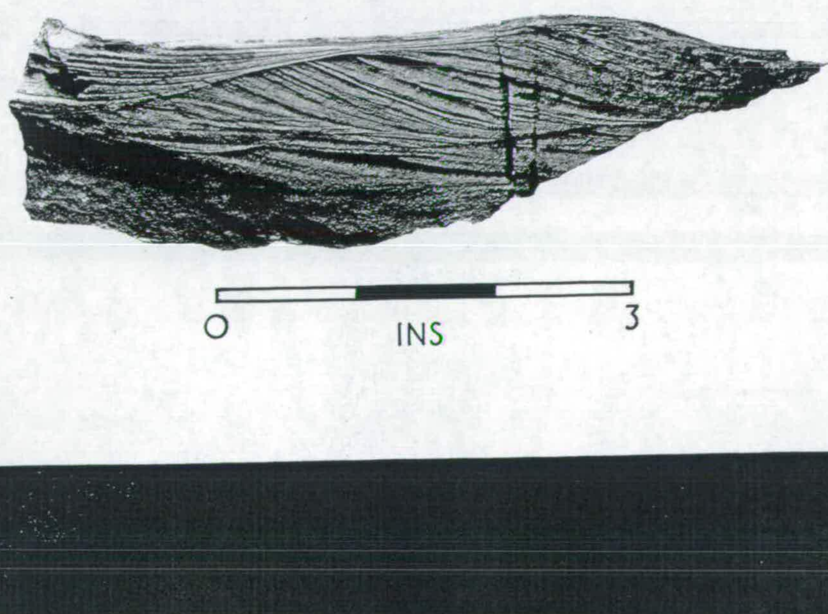
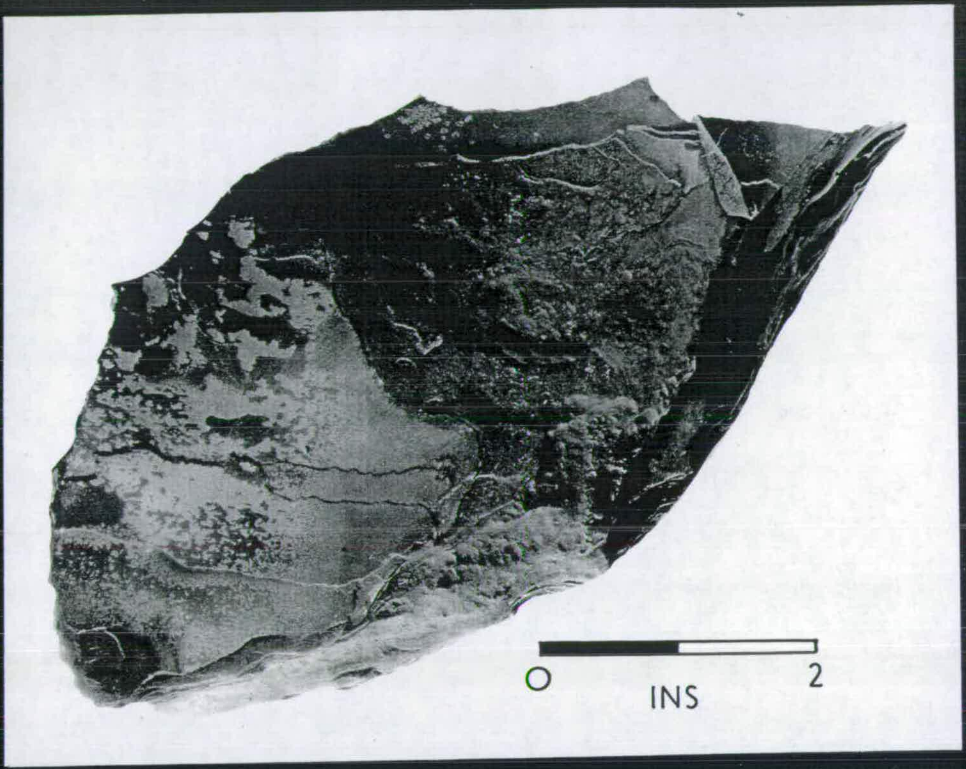


PLATE 21.

A. A calcareous nodule developed in a current-bedded unit at the top of a greywacke bed.

B. Rings of secondary red pigment formed by percolation of hematite outward from joint planes (Innerwell).

A



B

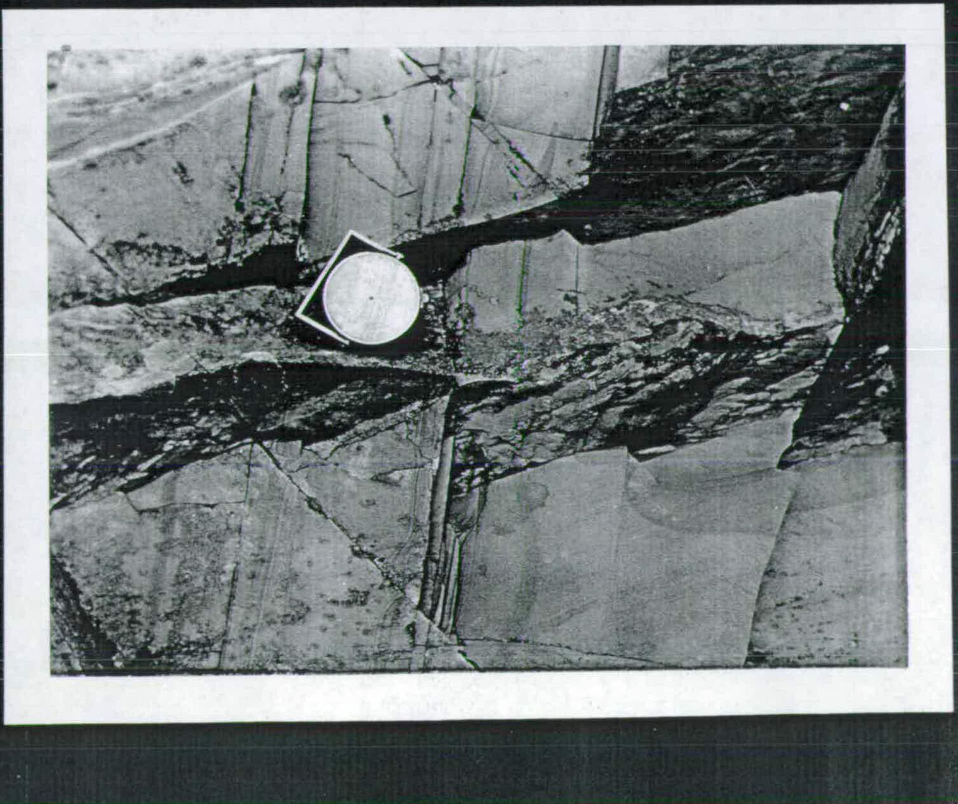


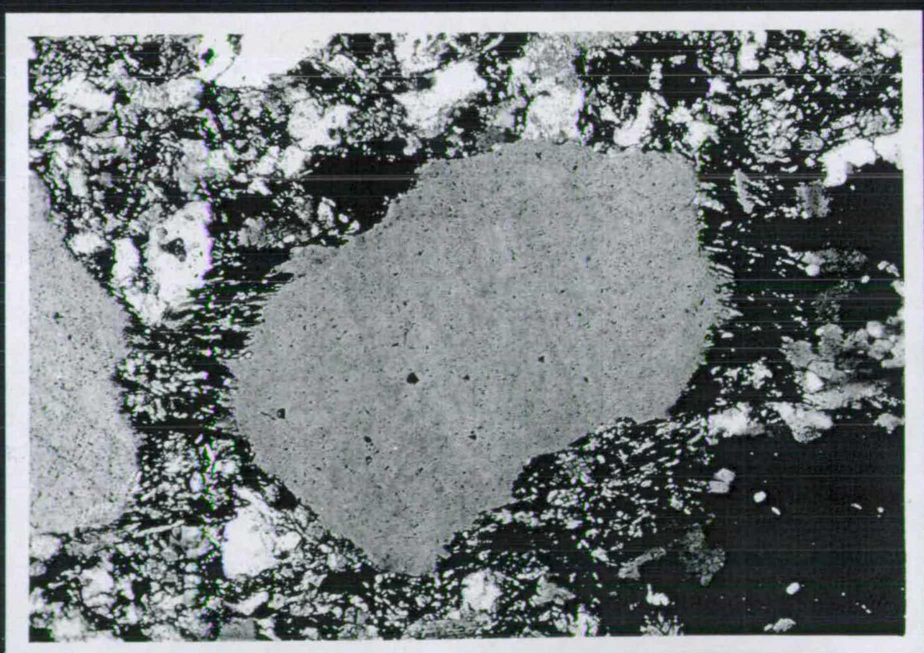
PLATE 22.

A. Flakes of muscovite with thin coatings of hematite (red micas from Hawick Rocks). Ordinary light, x450.

B. Development of foliation in a greywacke by recrystallisation of chlorite in the matrix. The large fragments of the greywacke remain unaffected, and the foliation therefore tends to pass around them. Ordinary light, x80.

A

B



In the present examples, the as~~s~~ymmetrical loading is thought to be due to deposition on a floor sloping towards the south-east, which induced loading with a trend biased in this direction.

Some of the larger flute-moulds at Palmallet Point show internal lamination which is almost planar and parallel to the bedding (Plate 14B). The same flutes have steep and usually overhanging side walls, and therefore present an acute problem as to their mode of origin. It is usually assumed that the overhanging walls were formed by simultaneous scour and fill by a turbulent current (Rücklin, 1938), but a turbulent current would be unlikely to deposit sediment with plane laminations. Nor can loading have taken place to any noticeable degree, since this would have distorted the laminae marginally. A possible explanation may be that the turbulent current rotated material in strongly localised vortices within the horizontal plane, so that simultaneous scour and fill was able to take place, and yet deposit horizontal laminae. The corkscrew form which some of the flutes display lends support for this hypothesis.

An exposure on Isle Head, near the village of Isle of Whithorn, shows terraced flutes (Ten Haaf 1959, p.28). These flutes are broad and shallow; internally they show no laminae, and the terraces reflect the differential resistance to erosion of laminae in the underlying mud. The plane nature of these laminae shows that loading has not occurred. About 20% of the flutes have a corkscrew form which indicates a left hand screw motion when viewed from above; none were observed with a right hand screw (Plate 15A). Smaller and less regular flute moulds occur together with longitudinal ridge moulds in a variety of complex forms.

Groove, chevron and prod moulds are relatively rare in the Whithorn area; the environmental significance of this rarity is discussed later (pp. 102-3). A number of groove moulds are well displayed at Corwar Quarry (456487). The grooves show a consistent asymmetrical loading, ie. they are loaded only on what is the southern side after reorientation of the bedding to a horizontal position. This asymmetry suggests that the grooves were formed by currents flowing over the floor of a basin which had a side-slope to the south. This indication of southerly side-slope is the same as that given by the asymmetrical loading of the flutes at Palmallet Point (p. 90).

Upper-surface ripple-marks are very common in the Whithorn area. They usually occur as ripple-drift multiple units, persisting through considerable bed thicknesses. The ripples are mostly transverse and are often asymmetrical, extending for some distance (although often with considerable irregularity) at right angles to the current direction indicated by the foreset laminae. A few cases have been noted of interference ripples, consisting of crests and basins with a more or less random orientation, but occasionally showing indications of two preferred directions (Plate 17B).

Loading of ripple marks is rare (Kelling and Walton, 1957 p.485), a fact which is probably due to their frequent covering by finer-grained material. Thus there is no tendency for the structures to be exaggerated by loading, although ripple moulds, formed in coarser-grained material above ripples might be expected to deform in this way. The rarity of ripple moulds (as opposed to the almost universal preservation of sole markings as moulds) suggests that currents which form ripples are invariably followed by periods of quiet sedimentation in which argillaceous material is deposited.

A noteworthy example of what are thought to be loaded transverse ripples may be found at Palmallet Point. The ripples (Plate 16B) occur on the top surfaces of beds which have already been mentioned (p. 90) for the profusion of flute moulding which they display underneath. The troughs of the ripples are exaggerated into sharp downward-facing depressions filled with shale, which closely resemble flame structures, apart from their inversion. The fact that the structures are ripples can be confirmed by tracing current bedded laminae along their length. When these laminae are seen in section (Plate 17A), the angle between topset and foreset laminae is found to be increased up to 80°, far beyond what could have been the natural angle of repose for this material (a fine silt). The inescapable conclusion is that the angles between the laminae have been exaggerated by post-depositional movements such as loading or slumping. However, there is little evidence of slumping, and the inverted flame structures penetrate the ripples approximately normal to the bedding. It is therefore suggested that loading has been the most important factor in the distortion of the ripples, and a possible manner in which it may have occurred is indicated in Fig. 24B. The actual mechanism of loading remains obscure, since a downward movement of shale into what is presumably a somewhat denser medium (silt) is involved. Perhaps the difference in density and water content after sedimentation were very slight, and the most significant physical difference between the two media was one of mobility. The more mobile shale therefore tended to move down into the silt as a response to some external stimulus, perhaps tectonic, perhaps due to the loading of the flutes at the base of the overlying bed.

Two other types of top-surface structures which should be mentioned are crescent marks and sand volcanoes. Crescent marks are formed by the current flowing around a solid object on the floor of the basin of deposition. They give a very accurate indication of current direction (Plate 18A), and it is therefore surprising that they have received little attention in the literature. The crescent shape is developed if the obstacle in the path of the current is above a certain size, which depends on the speed of the current and the grain-size of the sediment. When the current flows around an obstacle smaller than this critical value a single-tailed structure rather than a crescent is produced

(Plate 18A). It is evident that the term crescent mark is inadequate to describe all the structures which originate in the same manner. It is difficult, however, to find a simple alternative, and the term obstacle scour is tentatively put forward. In all the specimens collected it was found that the obstacle scours were present on successive beds through several inches of a siltstone succession (a maximum figure was not obtained). A dissection of one specimen showed that the obstacle approximated to a cylinder of fine sand, which persisted throughout the thickness of the specimen. The most feasible explanation of the smaller obstacles seems to be worm burrows, which obviously reached the surface, since they affected the currents. However, the obstacles are oblique rather than perpendicular to the bedding planes, an attitude which is not known for the burrows of living worms. A possible explanation may be that the oblique attitude was induced by tectonic deformation.

Sand volcanoes are fairly common in the area; two good localities are 700 yards north of Port Allen (478411), and The Barns (484368). The best examples show a central pit or crater, surrounded by a cone sloping gently outwards, which is smooth in most cases, but occasionally shows evidence of slumping (Plates 19A,B). It is thought that the presence or absence of a crater is merely due to the relative resistance to erosion of the material which forms it. Sections show that the crater is the upper end of a vent which extends to some depth in the sediment (Plate 18B). The arrangement of elongated fragments or trains of fine material in the vent indicates movement parallel to its length, which continues as an outward flow from the crater, and down the flanks of the volcano.

The volcanoes vary in diameter from ¼" to 4" but tend to be grouped into two sizes: above 2" and below ½" (Plate 19B). The smaller cones are probably satellites to the main volcanoes, since it is unlikely that such small vents could penetrate the full thickness of the beds concerned. The full extent of the main vents has not been determined since none are completely exposed, but it is likely that they originate in silts underlying the greywacke beds on which the cones are developed. These silts are in unstable equilibrium for some reason (probably high water content) and flow under the pressure exerted by the weight of the overlying greywacke bed. The impulse which initiates flow may be a seismic shock, and the location of the vents may be determined by load casting at the base of the greywacke, which is a similar pressure-induced phenomenon.

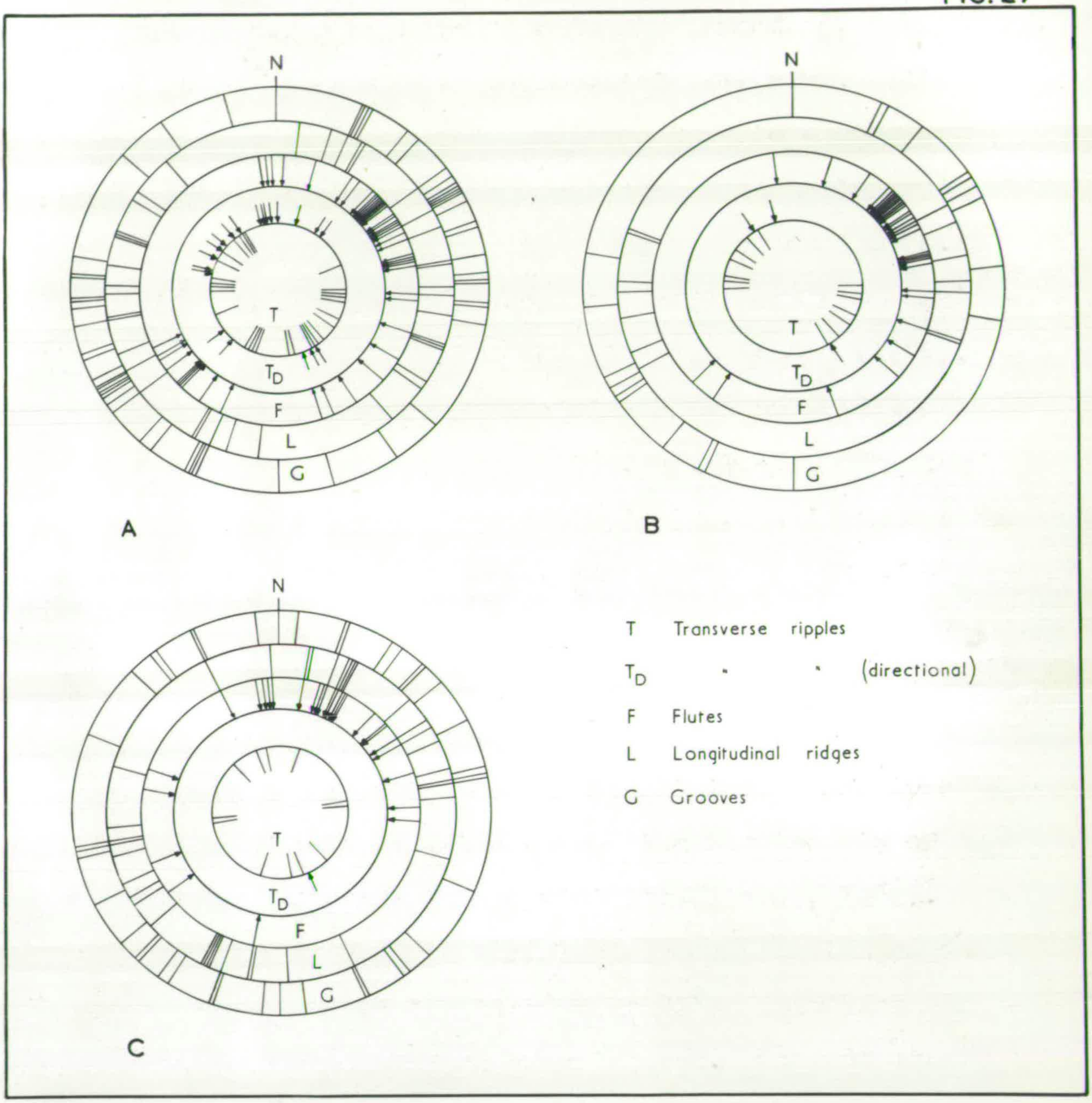
Evidence in support of the above views is provided by similar (but larger) sand volcanoes formed experimentally in modern intertidal sediments of the Nith Estuary (personal communication, J.B.Wilson). The volcanoes were produced by jumping up and down on waterlogged quick-sands and -silts, which induced upward movement of sand - laden water to form a central jet which rapidly built a cone measuring up to a foot in diameter. In some cases cone formation was associated with ring fracture, subsidence, and the development of satellite cones within the ring. Wilson found that volcanoes could only be produced in quick-sands and -silts, in which it is probable that a state of unstable equilibrium exists, which can easily be disturbed by sudden shocks.

Ancient sand volcanoes have been described from Carboniferous deltaic deposits in Ireland by Gill and Keunen (1957). Their association with greywackes has also been observed in the Hawick area of Roxburghshire (Warren 1962, pp.230-4). The sand volcanoes described by Warren lack central pits, and are ascribed by him to the overburden of sediment, and to the effect of slumping.

b) Current directions.

Patterns of current flow may be obtained from directional sedimentary structures after correction for the dip of the beds and the plunge of folds in the vicinity (Norman, 1960). However, the correction becomes very large when the plunge exceeds about 40°, and sedimentary structures near folds with axes steeper than this value have therefore been ignored. Current structures from steeply dipping areas in which fold axes are absent have been dealt with separately. The resulting distribution of current directions is shown in Fig. 27,A. A further diagram (Fig. 27,B), uses only current structures observed north of Shaddock Hole, the

FIG. 27



Reorientated sedimentary current directions:

A; Whole area.

B. North of Shaddock Hole.

C. From parts of the area lacking fold axes.

northern limit of F_3 folds. The distribution of current directions from this part of the area is more compact than that for the whole area, and it is therefore thought that the scatter of current directions obtained from the southern outcrops may be partly due to F_3 folding.

The current structures observed in areas of steep dip without fold axes were reorientated by assuming zero plunge, in the absence of any other information. The result (Fig. 27,C) shows that the mode for flutes has been rotated about 30° anti-clock wise with respect to the mode from areas where plunge data are available. This suggests that the 30° rotation represents the error resulting from the assumption of zero plunge. Taking the modal attitude of the beds to be vertical facing north, this error can be eliminated by assuming a fold plunge of 30° to the east.

A further difficulty is raised by the fact that the greywackes of the Whithorn area have undergone similar folding. Ramsay (1961) has pointed out that the unfolding of linear structures on similar folds requires a different technique to that employed for concentric folds, but Craig and Walton (1962) show that the assumption of similar instead of concentric folding would emphasise the same mode for current directions from Kirkcudbrightshire. Since, in the Whithorn area, there has been a concentric element in the folding (pp. 30-3), Norman's method has been taken as adequate. An additional error due to reorientation of strata by faulting is probably also present, and may be partly responsible for the wide scatter of current directions.

Conclusions.

Despite the errors listed above, it is still possible to discern certain maxima in the distribution of re-orientated current directions. Thus the flutes show a preferred orientation of currents travelling from north-east to south-west, with a subsidiary mode in the reverse direction. The main N.E.-S.W. transport of bottom-carried load in the greywackes is confirmed by the distribution of grooves and longitudinal ridge marks (although the latter show a rather wide scatter).

The ripples at the tops of the greywackes mostly indicate currents travelling from north-west to south-east, with a lesser mode in the reverse direction. The main direction of ripple transport is the same as that indicated for the bottom slope by asymmetrical loading of some of the sole markings.

These conclusions on current directions are largely in agreement with those put forward by Craig and Walton (1962) for Kirkcudbrightshire, but vary from the palaeogeographic reconstruction of Warren (1962) for the Hawick area.

c) Intrastratal sedimentary structures.

The rather poor development of ideal graded bedding in the greywackes of the area has already been mentioned (p. 81). Multiple grading is rare, and inverted grading has not been observed except where it affects limited parts of beds. There is no particular correlation between bed thickness and development of ideal grading, but there is a general tendency for coarser beds to show better-developed grading. The tops of the coarser greywackes are frequently fine, but the change in grain-size is usually more rapid towards the top of the bed and sometimes at the very base, than it is in the middle, Thus if grading is exhibited, it is mostly of the delayed type (Walton, 1956).

Convolute bedding and slump structures are not common in the Whithorn area, a fact which suggests that the sediments were laid down on a fairly flat floor. Structures termed pseudo-nodules have been ascribed to submarine slumping by Macar and Antun (1950) but have been re-interpreted by Kuenen (1958) as structures resulting from vertical movements due to loading. Kuenen has provided experimental evidence which suggests that pseudo-nodules are produced by loading, initiated by earthquake shocks. Good examples of pseudo-nodules occur at Isle Head, and are illustrated in Plate 20A. Their form suggests that they were produced by vertical rather than horizontal movements.

6. Origin, transport and depositional environment of the sediments.

a) Origin.

The lack of variety in clastic types and the relatively fine grain size of the Whithorn greywackes may be ascribed to a low-lying source area with few rock types, or perhaps to a prolonged transport history. When the greywackes of the Southern Uplands are considered as a whole, it can be seen that there is a general tendency for clast variety and grain size to decrease in the progressively younger strata to the south. This suggests that the features displayed by the Whithorn greywackes may be largely the result of steady erosion of the source area during Ordovician and earlier Silurian times. Greater distance from the source area may also have been a factor, but probably a less important one, since the fragments of the greywackes are angular (although small), and since the profusion of sole markings indicates strong currents. Also, there is little evidence of fundamental changes in the configuration of the geosyncline during Ordovician and Silurian times.

The origin of the fine-grained sediments is more problematic. The predominance of the green mudstones and siltstones and their association with the greywackes suggests that both were derived from the same source, although the modal current directions are mutually at right angles. The red beds sometimes show fine scale interbanding with the green beds, and it therefore seems unlikely that they represent different physical or chemical conditions in the basin of deposition. More likely, the red and green sediments have been derived from different source areas, the interbanding resulting from alternation of currents from the two areas, while the gradational contacts are due to mingling of material.

The commonly accepted source of red beds is a terrestrial area where lateritic weathering is taking place. Chemical (Table II) and clay mineral analyses (Fig. 26) of the Whithorn red beds do not lend particular support for a lateritic source, since the proportions of iron and kaolinite are no higher in these rocks than in the green beds. However, there is reason to believe that most of the iron in the red beds is in the form of hematite, probably originally derived from laterite, whereas the iron of the green beds mostly occurs as silicate. The basic difficulty is that there is insufficient knowledge of the conditions at source and at sedimentation which determine the deposition and preservation of red beds.

b) Transport.

The frequent occurrence of sole markings, especially flutes, on the greywackes, shows that the currents which deposited them were turbulent and strongly erosive. It is suggested that the rarity of ideal grading, which is usually characteristic of turbidites, is due to the comparative lack of variation in grain size. The relatively infrequent occurrence of groove and prod marks (both of which require tools) is probably due to a lack of fauna, and perhaps to the low-lying nature of the source area, rather than to the inability of the currents to carry tools.

Warren (1962) has emphasised the close connection between the greywackes of the Hawick area and the fine-grained beds deposited with them. He has therefore introduced the terms greywacke-mudstone and greywacke-siltstone, which are, in the present author's opinion, quite unnecessary. Since there is gradation from greywackes to green mudstones and from the latter to red mudstones and graptolitic shales in the Hawick area, Warren concludes that all these sediments were deposited from turbidity currents. This conclusion does not necessarily follow, for deposition of the fine material transported by the turbidity currents would be continuous with the quiet deposition of fine material from relatively still water. In fact most authorities are agreed that turbidity currents are comparatively rare events on the sea floor, whereas quiet sedimentation occurs almost continuously, although it accounts for only a small proportion of the sediment formed (Kuenen 1953). Transverse ripples in Kirkcudbrightshire and the Whithorn area show that the currents which affected the tops of greywacke beds ran perpendicular to those which transported the greywackes themselves. It is therefore likely that these sediments have been at least reworked by currents other than the main turbidity flows.

c) Depositional Environments.

The presence of graptolitic bands interbedded with greywackes shows that the whole sequence is marine. The frequent development of ripple marks, and the presence of (?) plant remains and a coral in the red siltstones suggest that the depth of water was not great - perhaps of the order of 200 feet.

The preservation of pigment in the red beds shows that these sediments were deposited in oxidising conditions, a conclusion which probably holds good for the green beds as well. However, the dark-grey graptolitic horizons indicate different conditions, for graptolites have not been found in any of the other sediments. The dark colour is presumed to be due to a higher carbon and sulphur content*, hence suggesting reducing conditions on the sea bed. Whether the presence of graptolites living and dying at the surface has produced reducing conditions on the sea floor, or whether the latter conditions have favoured the preservation of graptolites which were also present at other times, cannot be decided.

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* In fact the chemical analyses only partly confirm this assumption (Table).

POST-DEPOSITIONAL CHANGES

1. Introduction.

Pettijohn (1957, pp.648-9) has described the post-depositional chemical and mineralogical changes which affect sediments (other than metamorphism and weathering) under the general heading of diagenesis. Other authors exclude post-consolidation effects, but in the present work the term is used to cover changes occurring before and after consolidation. Most of the changes take the form of replacements of the original constituents by other minerals (Krumbein, 1942).

2. Carbonate Replacement.

The most extensive diagenetic changes in the sediments have been due to replacement by carbonates. Because of their greater porosity, the greywackes have been more readily affected than the fine-grained rocks, although the latter do contain carbonate, of which some is probably diagenetic (Table II). The altered greywackes have been microscopically examined for evidence of carbonate replacement, and a selection of these rocks has been examined by x-ray diffraction to determine the nature of the carbonate present*. Fig.28 shows the location of the samples

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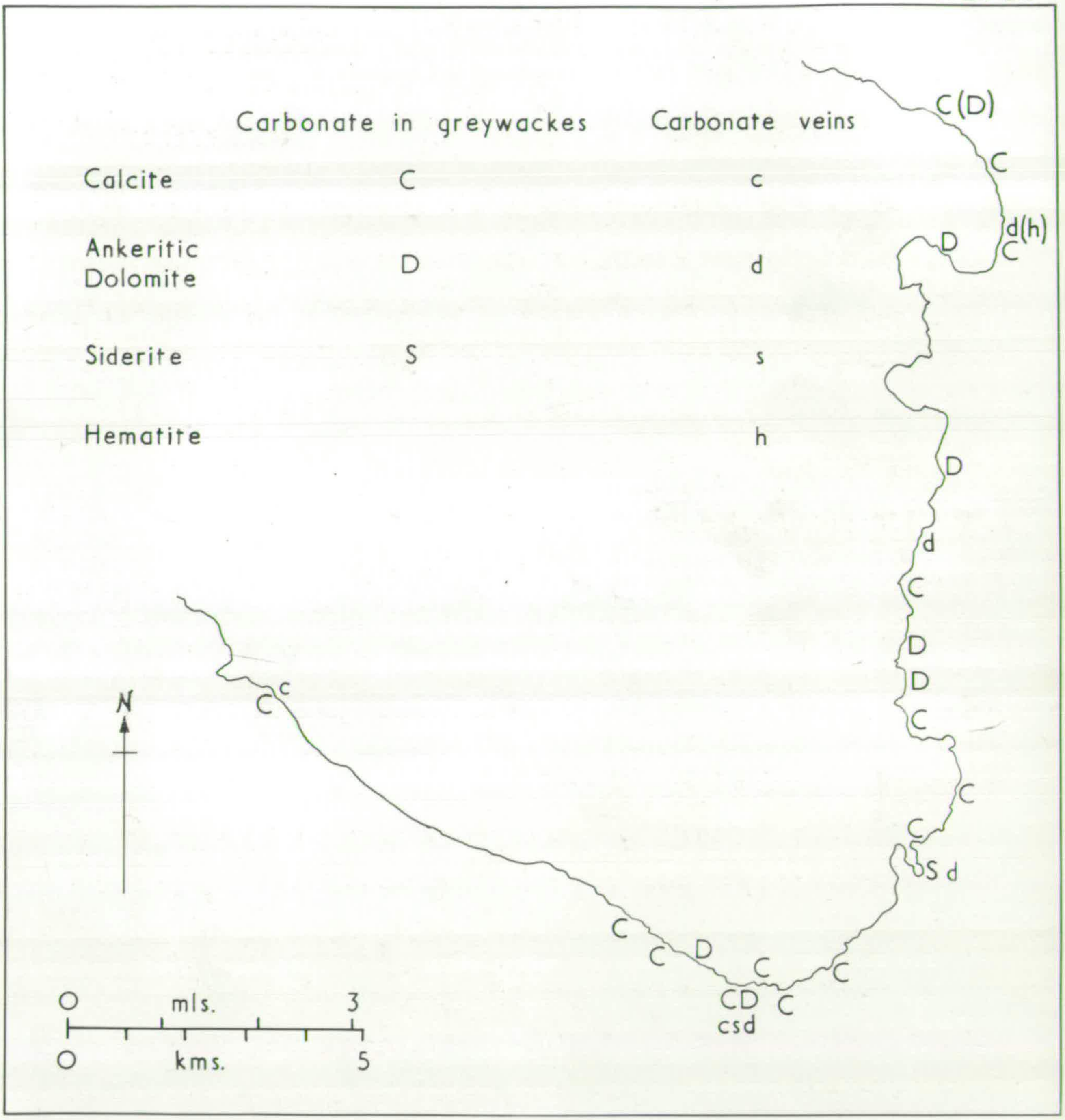
* A few grams of the rock were ground to a fine powder, which was made into a slurry with acetone. The slurry was transferred to a glass slide, and mounted on the diffractometer after evaporation of the acetone had left a smooth surface of powder.

FIG. 28



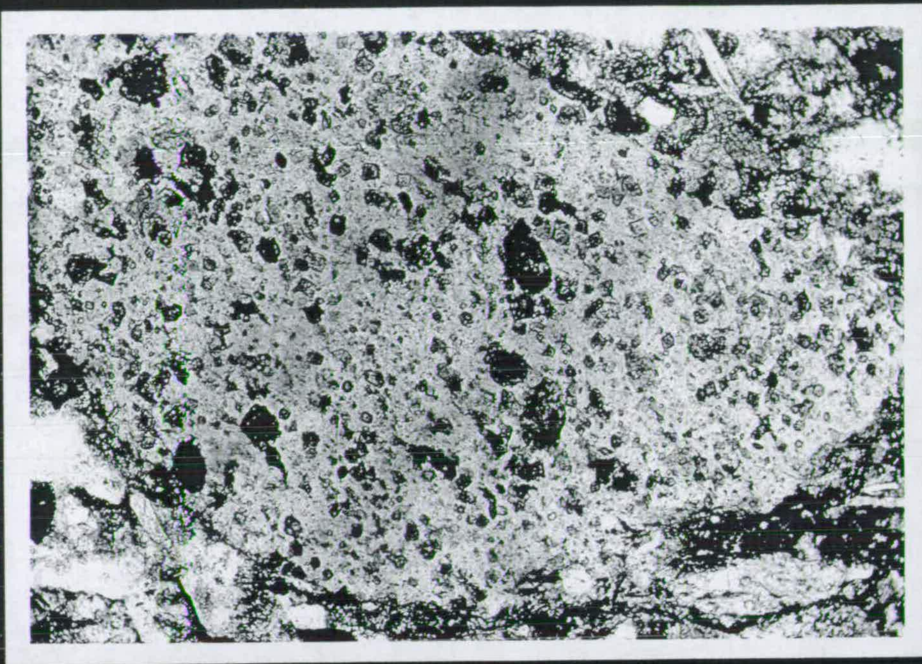
Locality map of greywacke and mineral vein samples tested for carbonates.

PLATE 23

A. Secondary dolomite in a fine-grained acid igneous fragment. Ordinary light, x 80.

B. Secondary dolomite arranged along a twin lamella in a fragment of plagioclase felspar. The dolomite crystals all have the same optical orientation. Crossed polarisers, x 450.

A



B

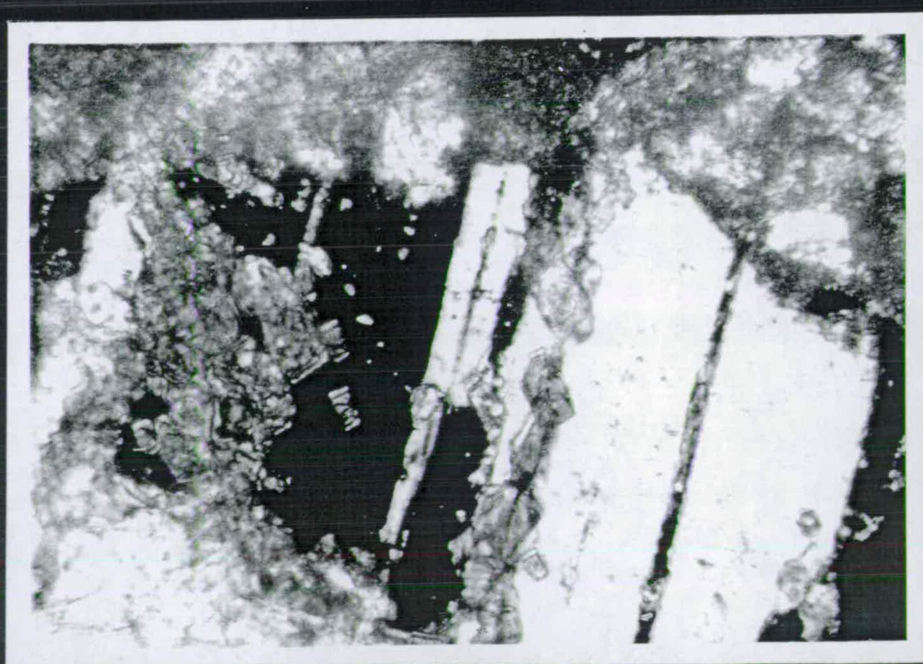
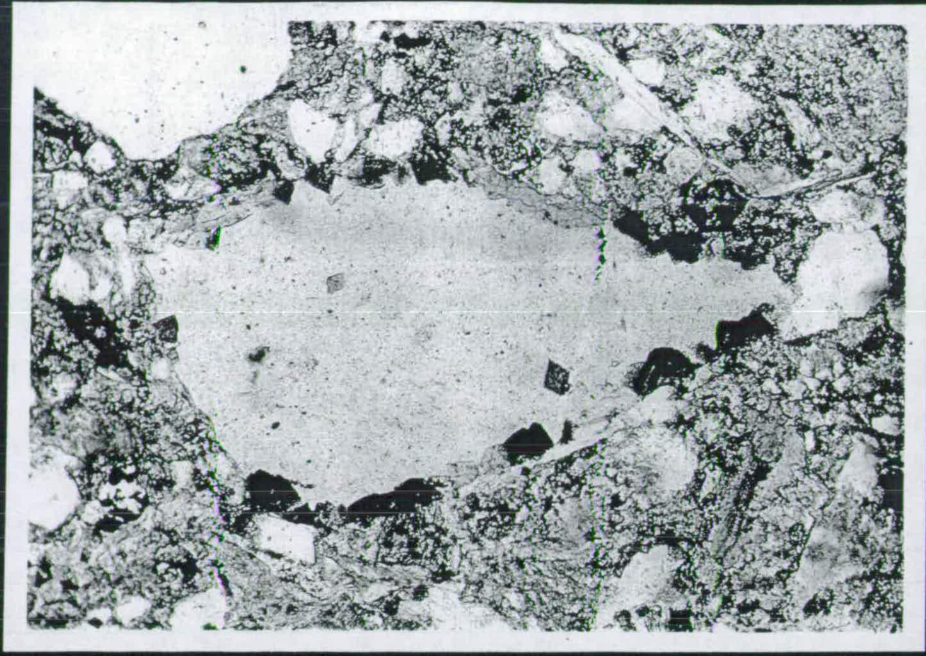


PLATE 24.

A. Pseudo-pleochroic calcite (?dolomite) in a fine-grained acid igneous fragment. Pleochroism ranges from a deep reddish-brown (the crystals at the lower margin of the fragment) to a pale straw colour. Ordinary light, x 80.

B. Secondary calcite in a granitic fragment. The felspar has been partly replaced by calcite, whereas the quartz (top left of fragment) is almost unaffected. Crossed polarisers, x 80.

A



B

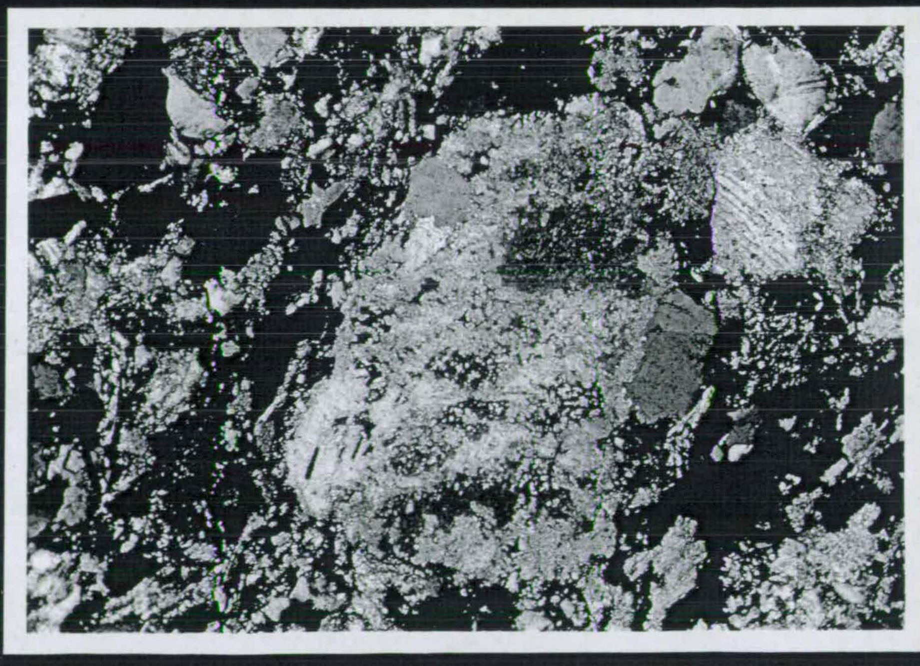
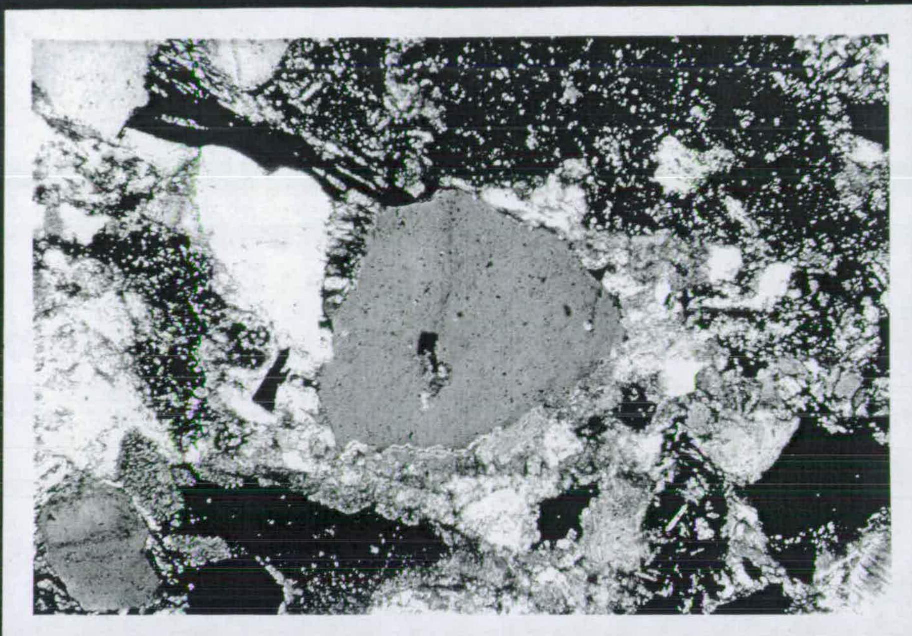


PLATE 25.

A. Secondary calcite growing around (and probably in part replacing) a quartz fragment. Crossed polarisers, x 80.

B. Secondary sericite in the margin of a quartz fragment. Crossed polarisers, x 80.

A



B

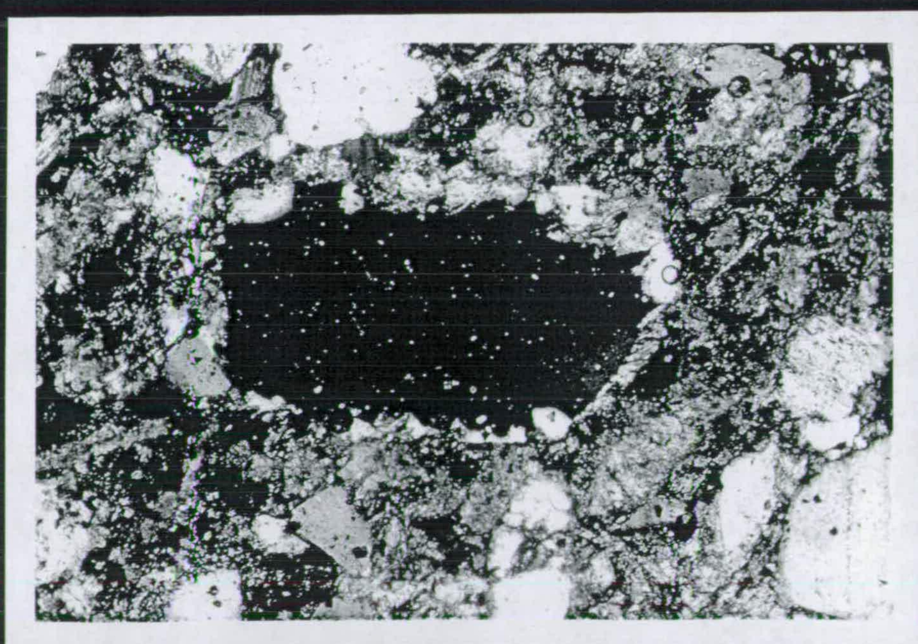
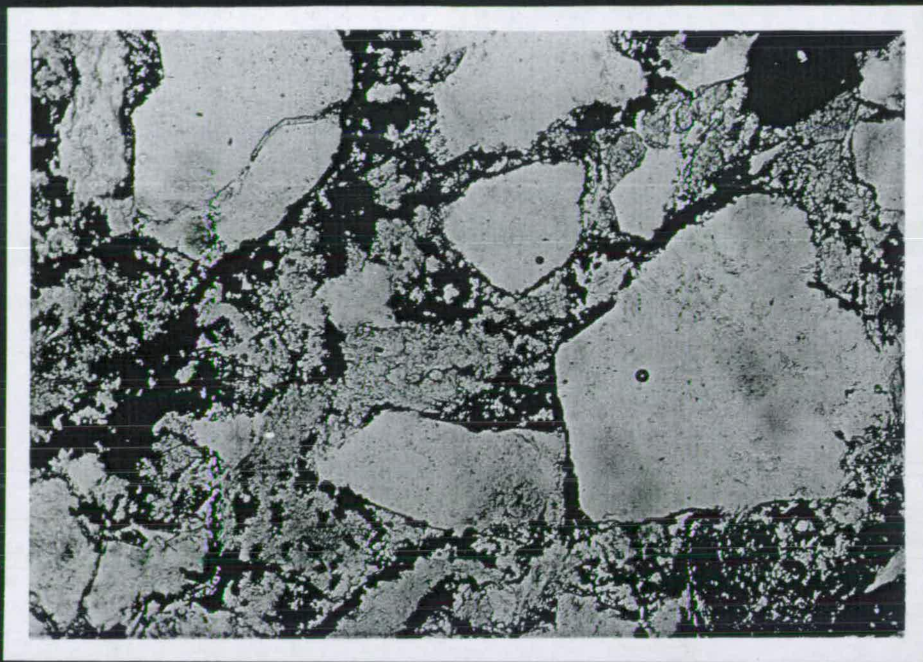


PLATE 26.

A. Secondary hematite in the matrix and around the borders of fragments in an altered greywacke. Ordinary light, x 80.

B. Secondary pyrite enveloping matrix and fragments in a greywacke. Ordinary light, x 80.

A



B

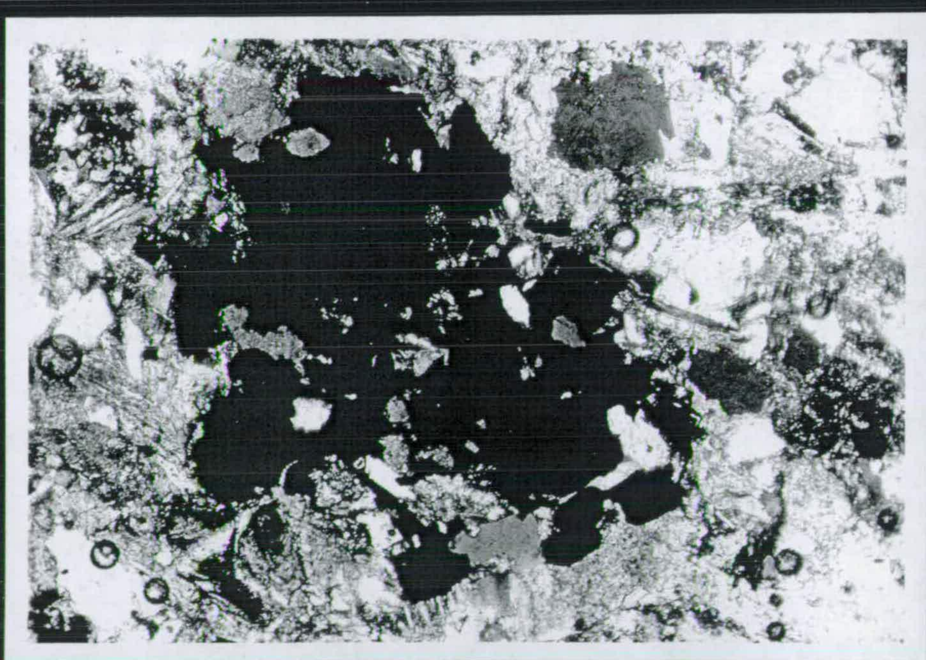
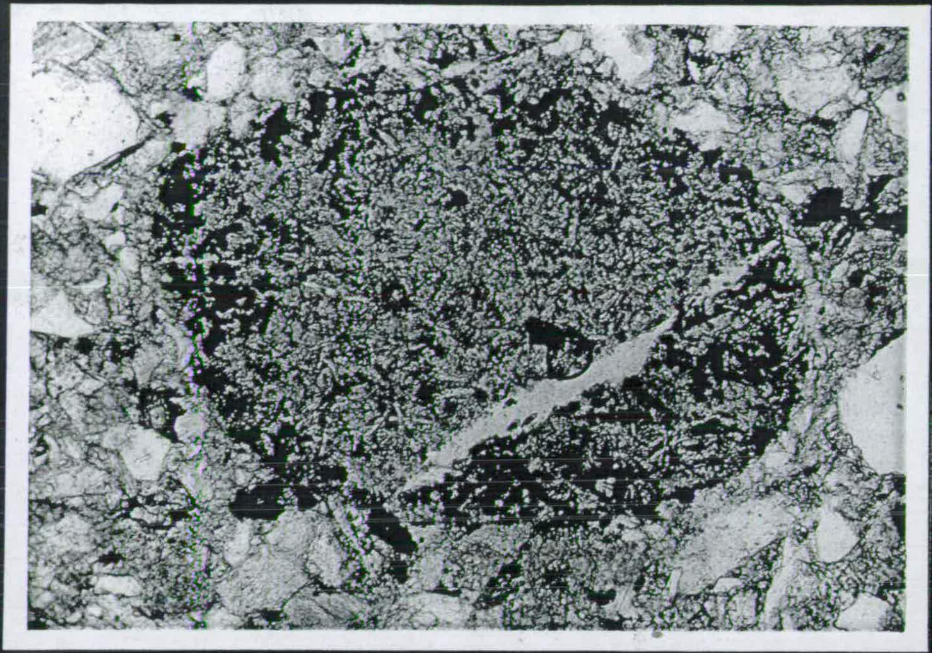


PLATE 27.

A. Spilite fragment showing marginal alteration due to the crystallisation of an ore mineral, probably pyrite. This could have occurred during the transport of the fragment, but may also have arisen after sedimentation, for the margin of the spilite could represent a particularly favourable site for the deposition of secondary pyrite. Ordinary light, x 80.

B. Secondary outgrowths of brown chalcedonic silica on angular siliceous fragments. Ordinary light, x 80. Crossed polarisers show that the fragments themselves are of chalcedonic silica, and probably represent an earlier replacement of what were originally quartz crystals.

A



B

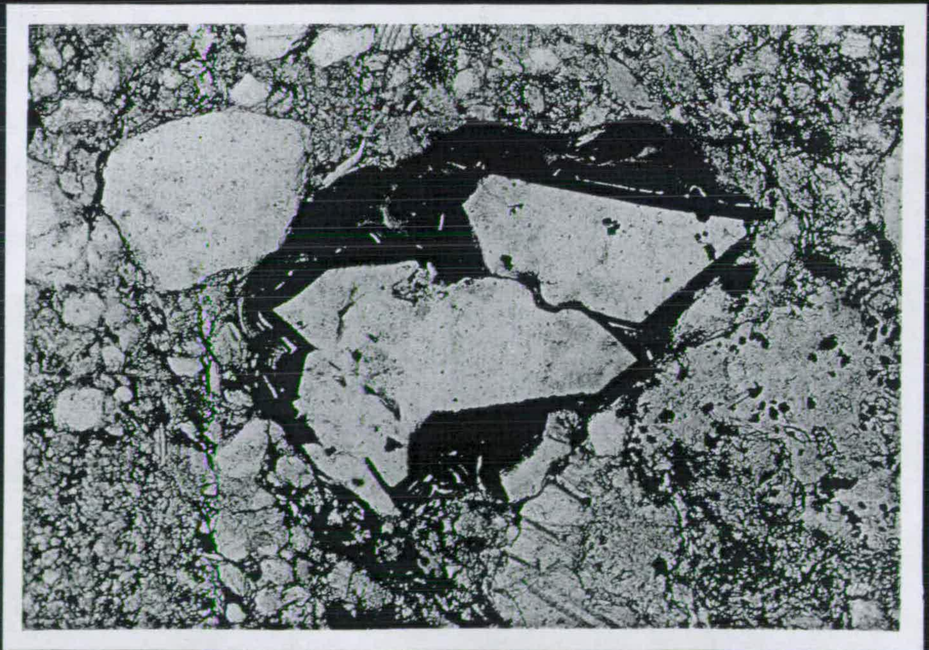


PLATE 28.

A. Secondary silica apparently replacing marginally a fragment of strained quartz. Crossed polarisers, x 80.

B. Secondary chlorite (? Penninite, ? Vermiculite) in a quartz fragment. Crossed polarisers, x 80.

A

B

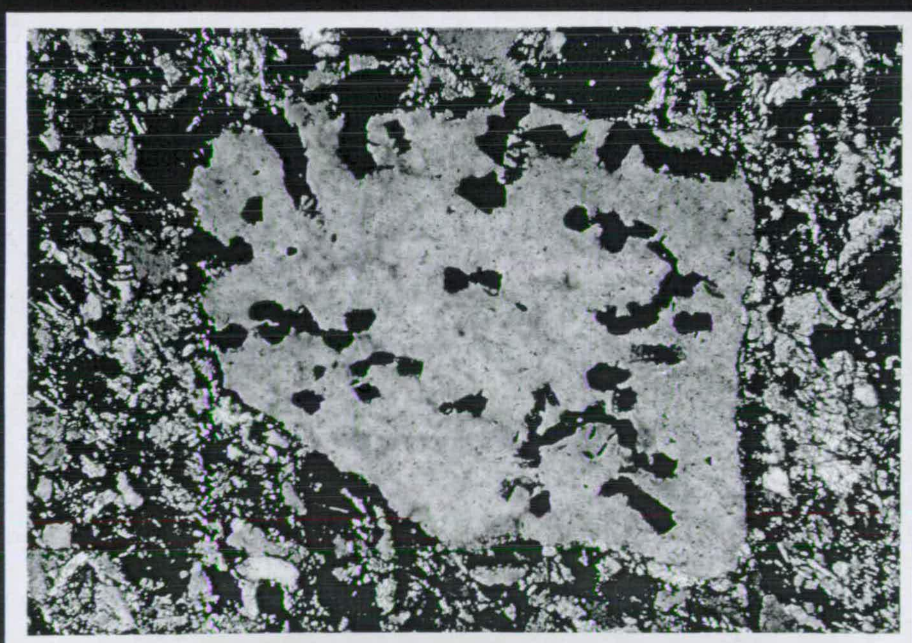
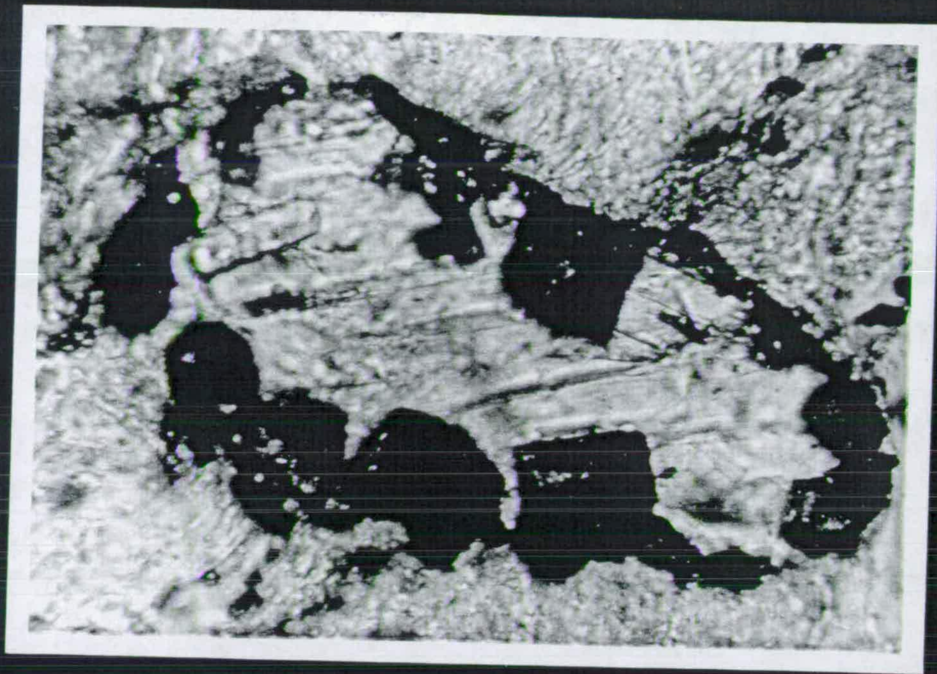


PLATE 29.

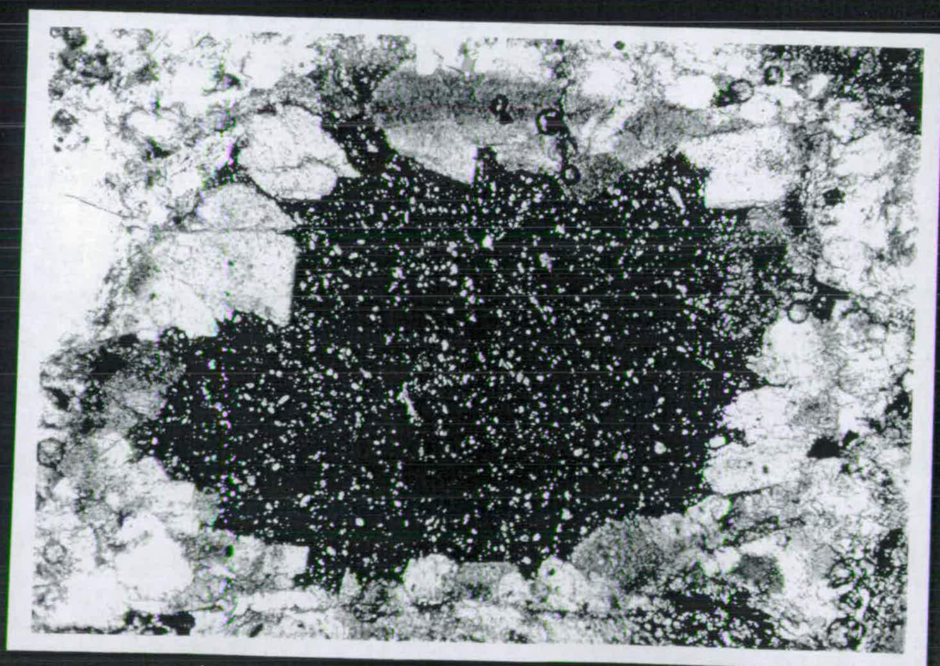
A. Secondary epidote at the margin of a grain of calcite. Crossed polarisers, x 450.

B. Replacement of a fine-grained acid igneous or chert fragment by carbonate, probably dolomite. The former margin of the fragment is marked by a ring of iron staining (top centre of picture), which indicates the later occurrence of iron replacement. Ordinary light, x 80.

A



B



tested in this way; it can be seen that there is no part of the area which is especially associated with either calcite or dolomite diagenesis. Dolomite can often be identified under the microscope by its tendency to euhedral shape (Plate 23), but it may be indistinguishable from calcite.

A few examples have been found of a secondary carbonate which is pleochroic from a light straw colour to deep reddish brown (Plate 24A). Similar pleochroism in calcite has been observed in lamellibranch shells (Hudson, 1962), and has been attributed to the absorptive effect of small amounts of finely-divided organic material. The present examples are therefore thought to be pseudo-pleochroic calcite with small amounts of minute impurities, but the euhedral nature of the crystals suggests dolomite as an alternative possibility.

A large variety of rock and mineral fragments in the greywackes have been partly or wholly replaced by carbonates. Felspars are particularly susceptible, and sometimes show replacement by euhedral dolomite crystals which all have the same optical orientation, and may be selectively placed along a twin lamella in the felspar (Plate 23B). Fine-grained acid fragments (igneous and sedimentary) are also commonly replaced by carbonate, and are the only types in which diagenetic pseudo-pleochroic calcite has been observed. In coarse acid igneous fragments the felspars frequently alter while the quartz remains comparatively unaffected (Plate 24B). Basic igneous fragments, argillaceous sedimentary fragments and the matrix are also susceptible to carbonate diagenesis. Quartz is usually unaffected but occasional grains show partial carbonate replacement (Plate 25A). Carozzi (1960, pp.39-40) suggests that selective corrosion of quartz grains may be due to marginal impurities on the quartz, such as hematite or illite.

The development of carbonate-rich nodules in the greywackes is a common diagenetic phenomenon in the Whithorn area. In some cases there is no apparent reason for the location of the nodules, but in others they form in the coarser foreset laminae of ripples. This presumably occurs because of the greater porosity of the coarser material, which facilitates the passage of carbonate-bearing ground water. Where the ripples have accumulated into ripple-drift bedding, the nodules traverse the beds obliquely, following the drift of the foreset laminae. Occasional instances have been found where the nodules have been drawn out parallel to cleavage, but in the vast majority of cases elongation of nodules is in all directions parallel to the bedding (ie. the nodules tend to be elipsoids, with the shortest axis normal to the bedding plane). The groups of nodules on the beds do not appear to have any linear trend parallel to the current direction (cf. Craig and Walton 1962, pp.108-9).

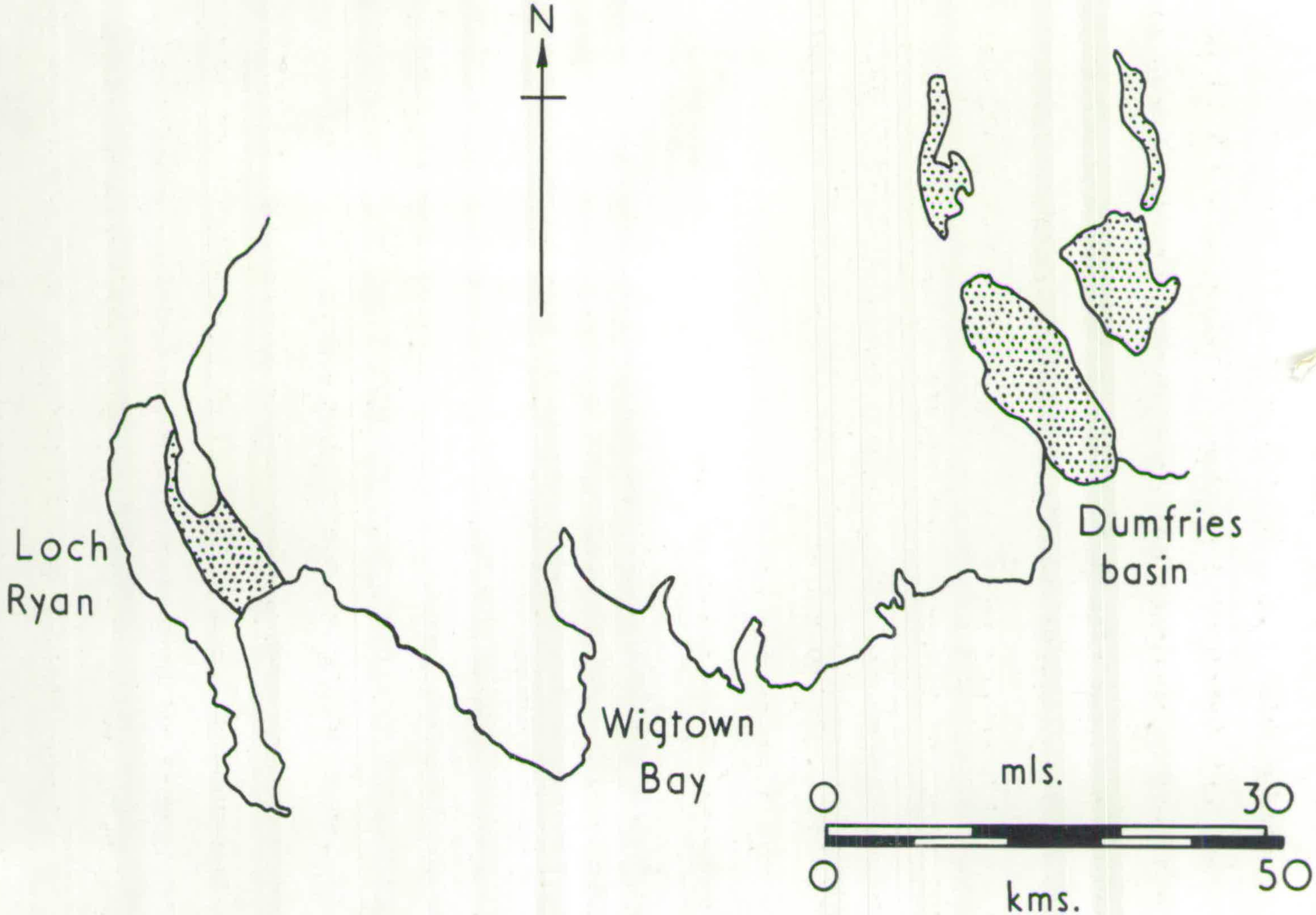
Examination of thin sections reveals as much as 70% diagenetic carbonate in greywackes of the Whithorn area, although the distribution of carbonate in the rock may be very patchy.

Concentration of carbonate in nodules may reach the stage at which the nodule is nearly pure limestone (Plate 2/A). This raises the question of whether the carbonate has been introduced from outside, or whether it was originally present in the sediment. Very few limestone fragments are present in the relatively unaltered greywackes, and a consideration of the other rock types present suggests that little dissolved carbonate could have been produced by their weathering. It therefore seems likely that much of the material has been introduced from external sources, and the frequency of carbonate veins in the area suggests an igneous origin. Calcite, dolomite and ankerite are all present as vein materials (pp. 119-121), and therefore constitute a ready source for the introduction of these minerals into the sediments. Warren (1962) reaches the same conclusion for the carbonated greywackes of the Hawick area.

3. Iron replacement.

The rocks of the north-eastern corner of the area, between Innerwell Fishery and Eggerness Point, have been particularly affected by the addition of iron. All types, igneous and sedimentary, have been cemented or partly replaced by iron oxide, but the fine-grained sediments show the highest degree of change. The resultant product varies from bright red to dull purple in colour, and can easily be distinguished from primary red beds by

FIG. 29



Map showing location and trend of New Red Sandstone basins in south-west Scotland.

the irregularity of colouration (Plate 21B). The red colour is strongest near joints, veins and faults, and cuts across bedding planes; it also affects the greywackes, which never show red colouration as a primary feature.

Thin sections of red greywakces from the Innerwell-Eggerness coast section show considerable development of hematite in the matrix. The clastic fragments bear evidence of replacement externally, and along cracks, but remain remarkably fresh internally (Plate 26A). Thus it appears that hematite selectively replaces or infiltrates the fine-grained components of the sediments, although it may slowly attack the coarser constituents as well. The effect is thus partly due to replacement, and partly cementation (Krumbein 1942). It is suggested that the strong hematite diagenesis seen in this part of the area is due to the former presence of New Red Sandstone sediments in the basin of the Cree Valley and Wigtown Bay. This basin has the same trend as similar basins to-day occupied by New Red Sandstone at Loch Ryan and Dumfries (Fig.29).

However, iron replacement is not limited to the north-eastern corner of the Whithorn area. It is locally developed near faults elsewhere, but is nowhere so intense, and has the yellowish colour of hydrated iron oxide. The hydration of the pigment may be the result of transportation over the land, followed by slow percolation down fault planes, whereas the red pigment at Innerwell was probably derived directly from an overlying source.

Another form of iron redistribution, which affects the sediments of the whole area, is the crystallisation of iron sulphides subsequent to sedimentation (Plate 26B). Cubes of pyrite are frequently observed in the green beds* (mudstones, siltstones and greywackes), while irregular masses (possibly marcasite) of up to an inch in diameter are found in the finer green beds. In the dark grey beds, graptolites have frequently been replaced by pyrite, which is also present as concretions and euhedra, but in the red beds there is little evidence of the presence of iron sulphides. It is unlikely that the material which has recrystallised to form iron sulphides was introduced from outside. It has probably been concentrated from dispersed material shortly after deposition of the sediment.

4. Silica Replacement.

Silica replacement is rare in the rocks of the Whithorn area. A few thin sections of greywackes have revealed chalcedonic silica replacing other mineral and rock fragments (Plates 27B, 28A). The rarity of silica replacement may be related to the resistance of quartz to other diagenetic changes; if this were otherwise then more silica would have been made available. Evidently silica from

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* Although chemical analysis of argillaceous green beds has not revealed the presence of sulphur.

igneous sources (numerous quartz veins are present) has had no diagenetic effect.

5. Other Diagenetic Minerals.

The replacement of quartz by chlorite is fairly common in greywackes of the Whithorn area, but it cannot be said to have affected a significant amount of the quartz present. The chlorite is green in ordinary light, with an anomalous blue interference colour which is usually ascribed to the variety Penninite. It takes the form of platelets or worm-like growths (perhaps Vermiculite) within the quartz, and is not especially concentrated around the edges of the quartz grains (Plate 28B).

One example has been found of epidote diagenetically replacing calcite (Plate 29A). Diagenetic epidote is rare, but has been noted by de Lapparent (1924).

6. Diagenetic sequence.

It has not been possible to erect a time sequence for the diagenetic formation of calcite, dolomite or silica. However, the marginal iron staining of diagenetic carbonate (Plate 29B) suggests that the period of iron replacement was later than the carbonate replacement. On the assumption that iron replacement occurred soon after deposition of the New Red Sandstone, the carbonate diagenesis was probably pre-New Red Sandstone in age.

7. Diagenesis and the formation of greywackes.

Cummings (1962) has revived the hypothesis originally put forward by Irving and Van Hise (1892) that greywackes evolve from felspathic sandstones by the diagenetic formation of a fine-grained matrix. This matrix consists of the break-down products (mostly clay minerals) of the less stable components of the original sediment, together with small fragments of these components released by the chemical changes.

The extent of diagenesis in the Whithorn area indicates the prevalence of active fluids since consolidation of the rocks. However, the fluids have largely induced carbonate and iron replacement; there is little evidence of the diagenetic formation of clay minerals which would also be expected if this is the way in which greywackes arise. In fact the clay mineralogy of the greywacke matrices and the associated fine-grained beds is essentially the same (Fig.26), which suggests that both were formed by the same process, ie. sedimentation. The sedimentary origin of the Whithorn greywackes is therefore upheld, but it would be wrong to dismiss diagenesis altogether, for it may well be a partial factor in the formation of some greywackes.

APPENDIX I: IGNEOUS ROCKS

1. Caledonian dykes.

a) Introduction.

The Caledonian dykes have in common a mineral suite which comprises quartz, alkali and plagioclase felspars, and ferro-magnesian minerals. The majority fulfil the definition of a lamprophyre given by Knopf (1936) in that they contain more than one third mafic minerals by volume. However, some of these cannot be assigned to one or other of Rosenbusch's lamprophyre categories (Hatch, Wells and Wells, 1949, p.352) because of difficulty in identifying the felspars, and/or the presence of more than one type of mafic mineral. Rosenbusch's classification has therefore been abandoned here in favour of a simpler grouping for the lamprophyres, while the non-lamprophyric dykes have been termed felsites (see p.47).

b) Felsites:

(Dykes with less than 1/3 ferro-magnesian material).

The ferro-magnesian material of the felsites is highly altered, and occurs as interstitial green glass or clots of chloritic material. The other constituents are quartz and

PLATE 30.

A. Equigranular felsite. Zoning in plagioclase felspar can be seen. Crossed polarisers, x 30.

B. Hornblende lamprophyre. Zoning can be seen in some of the hornblende phenocrysts. Biotite, largely altered to chlorite and epidote, is also present (X). The ground mass consists of quartz, plagioclase and alkali felspar. Ordinary light, x 30.

A

B

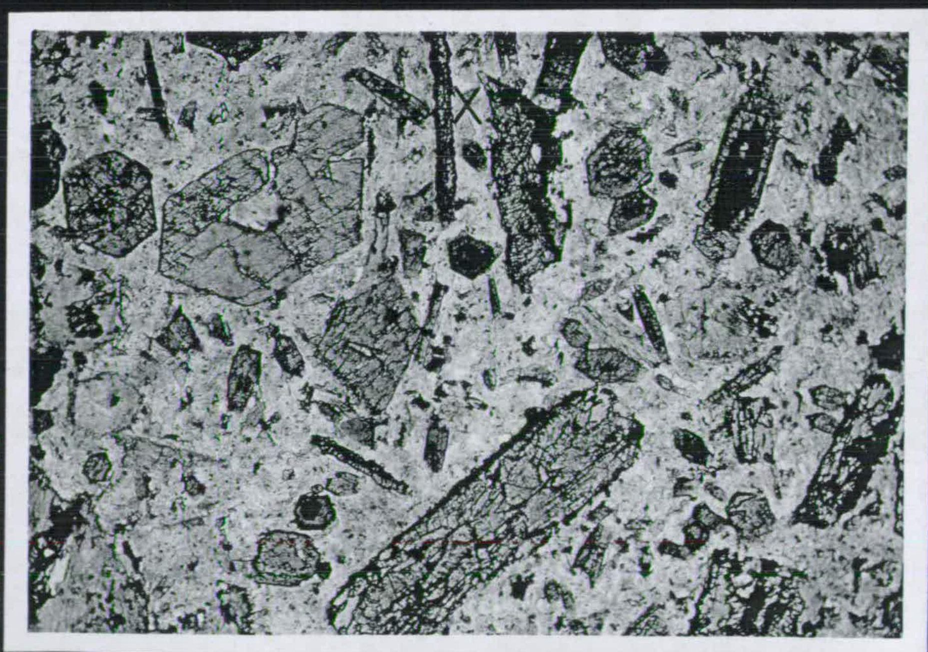
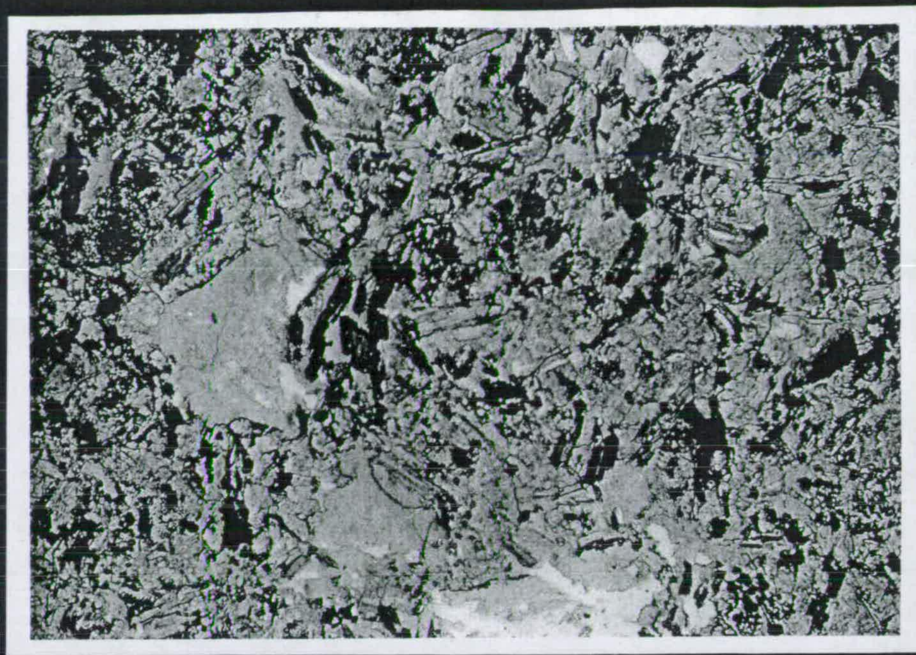


PLATE 31.

A. Biotite lamprophyre. The large clear areas are secondary carbonate. Ordinary light, x 30.

B. Analcite dolerite. A: large analcite phenocryst; T; titanangite; P: plagioclase; I: ore mineral (probably ilmenite). Ordinary light, x 30.

A



B

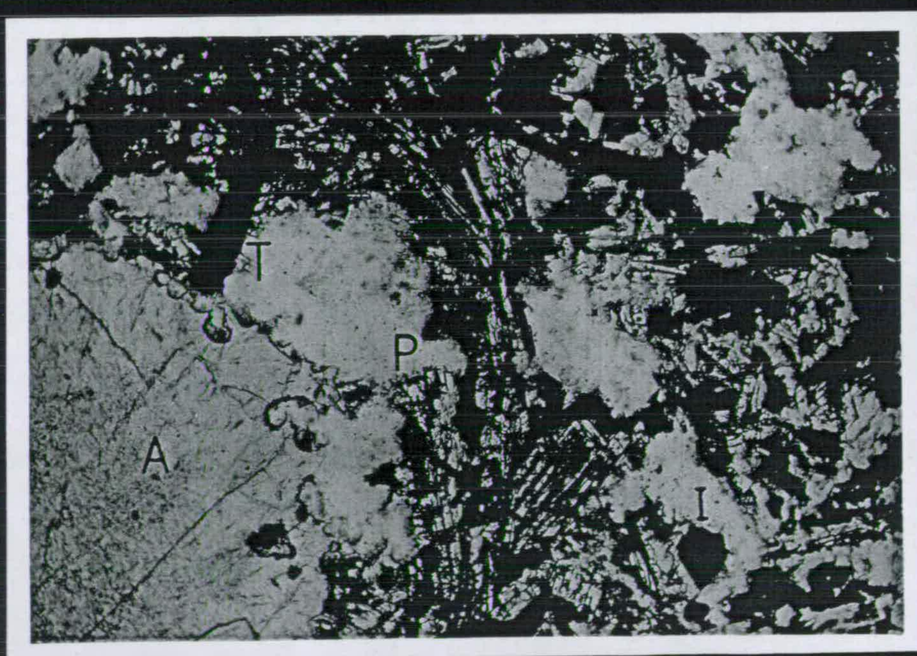


PLATE 32.

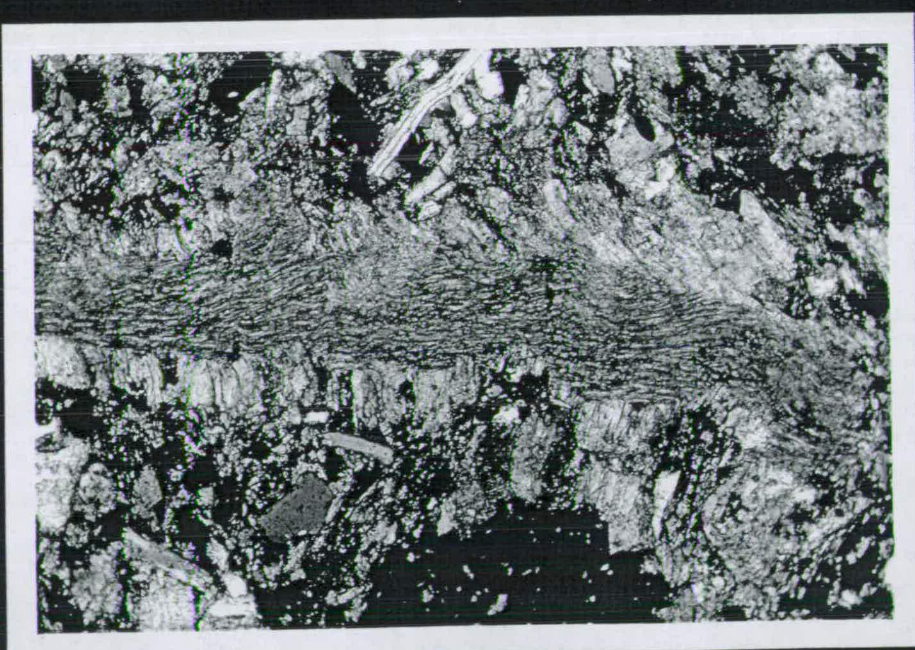
Mineral veins.

A. Carbonate vein cutting a quartz fragment. The vein has forced the fragment apart, and induced strain lamellae in it. Crossed polarisers, x 80.

B. Carbonate vein with secondary outgrowths of carbonate parallel to the foliation of the matrix throughout the rock. Crossed polarisers, x 80.

A

B



felspar, of which plagioclase and alkali felspar occur in roughly equal amounts. The plagioclase is frequently zoned from oligoclase cores to rims of almost pure albite. The average grain-size of the equigranular felsites is about $\frac{1}{2}$ mm, whereas the phenocrysts of the porphyritic felsites may reach an average diameter of 1 mm, and are set in a finer ground-mass.

Two varieties of felsite are recognisable in hand specimen on account of their colours: pink and greenish. The difference is due to ferromagnesian content (the greenish felsites are closer to lamprophyres in that they contain more ferromagnesian material). The two varieties of felsite may represent the two stages of felsite intrusion observed by Holgate (1943) in the Mull of Galloway, but there is no supporting structural evidence in the Whithorn area.

c) Hornblende lamprophyres.

(More than 1/3 ferro-magnesian minerals; hornblende present).

The hornblende lamprophyres are the least altered of the Caledonian dykes (Plate 30B). The hornblende usually occurs as euhedral phenocrysts, which usually show zoning and pleochroism in shades of brown and green when fresh, but are sometimes altered to chlorite and ore minerals. Some of these dykes contain biotite, but in all cases except one it is subsidiary to the hornblende.

The plagioclase felspar of the hornblende lamprophyres lies mostly within the albite - oligoclase range; sodic andesine has been observed in one specimen. The alkali felspar is not easily identified on account of alteration, but Reynolds (1931, pp.109-111) has put forward reasons for suggesting that anorthoclase is the alkali felspar of similar dykes in the Ards Peninsula. The felspar content of the Whithorn dykes varies from almost pure plagioclase to a 3:1 predominance of alkali felspar.

d) Biotite lamprophyres.

(More than 1/3 ferro-magnesian minerals; hornblende absent).

The biotite lamprophyres (Plate 31A) are more highly altered than the hornblendic types. The biotite usually occurs as phenocrysts, which are pleochroic when fresh, but lose colour and pleochroism in the first stage of alteration. As this continues, the biotites become partly or wholly replaced by chlorite or chlorite and epidote. The ground mass is fine-grained and highly carbonated. Quartz and felspar can sometimes be distinguished, but in no case is it possible to determine the type of felspar.

e) Inclusions.

A feature frequently observed in both types of lamprophyre is the presence of inclusions. A few of these are angular fragments of baked shale or greywacke, torn from the country rock during intrusion of the dykes. The remainder are rounded, and have obviously been in contact with the dyke magma for a longer period. The vast majority of these rounded inclusions are almost pure quartz, which is very like vein quartz in thin section. Turner and Verhoogen (1960, p.255) suggest that quartz inclusions are the undigested remains of country rock partly assimilated during the formation of lamprophyric magma. Granitic inclusions have been found in a lamprophyre at Sliddery Point (486441).

f) Petrogenesis.

It is likely that the difficulty experienced in classifying these rocks is largely due to close genetic relationships. They are probably all members of a differentiation trend which has followed a progressive enrichment in ferromagnesian minerals from a parent magma which was granitic or granodioritic in composition (Reynolds 1931, pp.159-163). There seems to have been little change in felspar composition throughout this series for the felsites and lamprophyres show a similar range in felspar types. The most obvious sources of the parent magma for the dykes are the Caledonian plutonic bodies, which are mostly granodioritic. However, the Cairnsmore of Fleet mass, the nearest to the Whithorn area, is said to be granitic in composition (Pringle 1948, p.49), although comparatively little is known about it. The presence of granitic inclusions in a lamprophyre at Sliddery Point suggest the likely derivation of the dykes from the Cairnsmore mass, or from a related plutonic source. However, there is a general tendency in recent literature to deny any direct relation between granites and lamprophyres (Turner and Verhoogen, 1960, p.254). Instead, lamprophyre magmas are thought to have risen independently along fractures resulting from the granite emplacement, and in some cases a considerable interval between the two periods of intrusion has been shown.

g) Alteration of the dykes.

Reynolds (1931))suggests that the carbonation of the phenocrysts and matrix of lamprophyres in the Ards Peninsula is due to autometasomatism. Read (1926) and King (1937) also invoke this process to explain the alteration of lamprophyres in Wigtownshire and Kirkcudbrightshire respectively.

Widespread dyke alteration similar to that described by Reynolds has been observed in the Whithorn area, and has affected the biotite-lamprophyres and felsites in particular. The alteration is ascribed to late magmatic rather than post-magmatic changes, since the carbonate diagenesis of the sediments can also be explained by the late-stage processes of the dykes. The alternative possibility, that both sediments and dykes have been altered from an unknown external source is less satisfactory, but cannot be altogether dismissed. The quartz-calcite-dolomite veins of the area could be the means whereby replacement materials were introduced from a deep-seated source. At any rate, it is suggested that the alteration of the dykes, whether autometasomatic or post-magmatic may be equated with carbonate replacement in the sediments and the quartz-calcite-dolomite veins.

Undoubted post-magmatic alteration of intmusions may be seen in the Innerwell-Eggerness coast section, where most of the rocks present have been altered by percolating iron-rich solutions. Lamprophyres show replacement of ferro-magnesian phenocrysts and part of the matrix by iron oxides, whereas the felsites appear to be comparatively unaffected.

2. <u>?Tertiary Dykes</u>.

Five dykes of analcite dolerite have been ascribed to a Tertiary intrusive phase (pp. 52-3). A typical example contains 10% euhedral analcite, 15% pleochroic, colour-zoned titanaugite, and 60% plagioclase zoned from labradorite cores to andesine rims. The remainder consists of ore minerals and a turbid ground mass, which may contain altered analcite. The texture is sub-ophitic with the analcites occurring as large phenocrysts (Plate 31 B).

3. Mineralisation.

a) Quartz - Calcite - Dolomite (?Caledonian).

The commonest mineral veins in the area consist of quartz and calcite, which are found separately and together. The calcite is sometimes associated with dolomite*; all three minerals are therefore assumed to be approximately the same age. Plate 32B shows a carbonate vein in a thin section of a greywacke; secondary carbonate has been added later, parallel to the foliation which affects the matrix throughout the rock. This foliation was formed in the Main fold phase, or in the F_3 fold phase, and therefore suggests that the carbonate vein was formed before F_3 folding, and must therefore be Caledonian in age.

A thin section of one quartz-calcite vein shows 20% plagioclase felspar with a composition approximating to albite. The development of felspar in a mineral vein appears to be a rather rare occurrence (Dunham, 1959, pp.19-20) and indicates crystallisation at a temperature intermediate between magmatic and pneumatolytic conditions, probably during one of the Caledonian igneous phases.

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* Dolomite may sometimes be distinguished from calcite by its crystal form, but x-ray identification is frequently necessary.

Two large masses of calcite which are thought to be a form of mineral vein are exposed on the cliffs midway between Castle Feather and Burrow Head. One measures about 20 yards by 6 yards, extending down into the surrounding sediments to an unknown depth, and is bounded by irregular shears. The calcite is coarsely crystalline, and has two forms: grey calcite, which is traversed and displaced by veins of white calcite closely resembling that found as veins in the country rock. At the edges of the mass, blocks of greywacke and shale are intimately mixed with the calcite, and have been carbonated by it. The second mass is more extensive and more highly sheared into wedges (together with the country rock), but otherwise resembles the first calcite body. The origin of these masses as solid bodies brought to their present position by faulting is discounted, since this could not explain the carbonation of the country rock. They are thought to be mineral veins of rather unusual proportions, emplaced by movement of magmatic fluids along fault planes. However, analyses of the calcite show amounts of copper, zinc and lead which are not in excess of those to be expected in sedimentary carbonates.

b) Barytes - Dolomite - Chalcopyrite (?Hercynian).

Thin veins of barytes are found in various parts of the area, but the only locality at which they reach appreciable size is 300 yards east of Castle Feather, where veins of up to one foot in thickness occur. The barytes is white and orange-pink, and is associated with small amounts of chalcopyrite, which has altered to azurite and malachite by secondary processes. Veins of ankeritic dolomite are also present, parallel to the barytes veins, and are thought to have been formed in the same period of mineralisation. Caledonian hornblende lamprophyres at the same locality have been heavily carbonated by the dolomite veins. Because of this, and the similarity to Hercynian mineralisation at Leadhills and elsewhere (Temple 1956, pp.107-9, Moorbath 1962, p.325), the barytes - dolomite - chalcopyrite veins are thought to be Hercynian.

c) Alteration of mineral veins.

Between Innerwell and Eggerness, where the rocks have been almost universally stained with iron, bright red mineral veins occur, which x-ray investigation shows to be hematite-enriched ankerite. Since veins of this type are not found elsewhere, it is assumed that they have been formed by the partial replacement of ankerite or calcite by hematite.

APPENDIX II: MICROMETRIC ANALYSIS.

Specimens of greywacke considered sufficiently coarse-grained and free of alteration were micrometrically analysed using a Swift point counter. Approximately 1300 points were counted for each of the specimens, which were collected at the localities shown in Fig. 25 .

A . Wenlock Rocks

No.	Qz.	Fspr.	Acid ign.	Basic ign.	Sed.	Metamorphic	Matrix
124	34.3	5.4	6.1	5.0	8.3	0.8	40.1
126	20.7	3.8	5.3	4.8	6.9	-	58.4
125	25.7	2.8	3.5	5.6	10.8	-	51.6
123	28.5	4.9	5.0	2.6	4.0	0.3	54.7
119	25.2	4.4	4.3	3.3	8.8	0.2	53.7
124C	27.5	4.0	3.1	2.1	4.5	0.7	58.0

B. Hawick Rocks.

1. Southern Quartz-rich Member.

No.*	Qz.	Fspr.	Acid ign.	Basic ign.	Sed.	Metamorphic	Matrix
70	34.4	3.0	10.4	6.8	12.4	1.4	31.6
87	28.3	4.2	16.6	7.0	13.9	1.0	29.0
68	30.3	3.5	8.5	6.2	16.4	0.8	34.2
73	24.4	3.7	15.1	7.3	22.2	-	27.3
128	33.1	3.4	12.2	6.1	17.4	0.6	27.2
92B	27.8	2.8	13.3	5.6	14.4	-	36.0
92A	20.6	1.2	19.5	4.9	20.5	0.1	33.2
74	34.4	3.9	4.7	1.3	13.9	0.6	41.2

2. Intermediate Member.

66	19.8	2.8	16.3	5.9	25.0	0.5	29.7
63A	26.2	2.2	16.5	7.2	16.6	0.5	30.8
63B	28.3	4.9	6.4	8.8	26.1	2.7	22.8
138	24.1	0.7	10.9	8.6	25.2	2.6	27.9
93	29.6	4.8	7.3	7.1	18.0	0.7	32.5
139	28.3	1.7	6.7	7.2	19.3	2.5	34.3
58	26.4	2.7	16.0	7.0	16.8	2.8	28.3
55	21.4	1.8	15.7	7.4	23.0	1.1	29.6
53	26.0	4.5	16.4	6.0	20.9	3.0	23.1
102	24.2	3.2	12.8	9.2	25.1	1.8	23.7
103	24.5	3.8	11.8	10.4	19.3	1.9	28.3
104	19.4	2.2	14.1	7.1	26.6	3.3	27.4
8	20.3	3.9	15.3	13.3	16.6	1.9	28.7

* Hawick specimens are arranged in order from south to north across the strike.

3. Northern Quartz-rich Member.

No.	Qz.	Fspr.	Acid ign.	Basic ign.	Sed.	Metamorphic	Matrix
4	32.9	4.3	10.3	5.3	15.0	1.0	31.2
191	32.9	2.1	7.7	17.0	12.3	0.7	27.2
111	29.8	2.4	9.2	6.4	9.3	1.0	41.9
182	30.8	3.6	10.2	5.8	12.7	0.7	36.2
12	33.0	2.4	7.9	5.4	8.7	1.9	40.7
279	30.6	3.3	6.9	6.9	6.4	0.9	45.0
190	31.9	3.6	9.8	11.0	19.6	1.2	22.9
116	27.3	2.5	8.3	12.0	9.8	1.1	38.9
118	30.0	2.7	12.1	4.5	5.9	0.4	44.5
14	29.8	5.8	11.5	8.6	11.1	1.1	32.2
180	39.8	4.9	6.5	3.2	6.3	0.2	39.1
23	35.2	5.0	17.6	5.7	9.6	0.6	26.1
169	28.4	2.6	3.2	2.9	4.3	1.2	57.4
32	35.0	3.2	8.4	5.6	11.2	0.9	35.7
40	38.1	5.2	9.4	6.6	14.9	1.5	24.3
46	35.7	4.6	6.7	3.3	11.9	0.9	36.9
44	29.3	7.6	7.5	4.3	10.6	0.6	40.0

C. Garheugh Rocks

No.	Qz.	Fspr.	Acid ign.	Basic ign.	Sed.	Metamorphic	Matrix
7*	37.6	6.8	7.8	5.4	6.5	1.8	34.0
15	33.5	3.5	6.3	5.0	16.7	3.8	31.3
4	39.9	7.9	13.3	4.7	2.8	0.1	31.3
6	43.1	6.5	6.9	6.0	11.9	1.5	24.1
8	37.1	4.6	6.3	7.2	14.0	1.8	29.0
2	33.8	11.6	11.6	8.3	4.9	0.5	29.3
1	27.7	6.6	15.0	8.4	2.7	0.2	39.4

In order to test the significance of these members the mean values (M) and standard deviations (σ) of the quartz percentages were calculated:

A <u>Wenlock Rocks</u>

$M_W = 27.0, \quad \sigma_W = 4.09$

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* Numbers refer to specimens quoted by Gordon 1962.

B Hawick Rocks.

$M_H = 28.3 \qquad \sigma_H = 5.35$

Southern Member: $M_{H1} = 29.2$

Intermediate Member: $M_{H_2} = 25.0$

Northern Member: $M_{H_3} = 31.3$

C Garheugh Rocks.

$M_G = 36.1, \quad \sigma_G = 4.62$

On applying Student's "t" test, it was found that there was no significant difference between the quartz percentages of the Hawick and Wenlock Rocks, but the difference between the Hawick and Garheugh Rocks nearly reached the 0.1% significance level.

The results of the micrometric analyses were then recalculated so as to eliminate the matrix, and it was found that the new quartz percentages brought out more significant differences between the members. The recalculated means and standard deviations are as follows:

A Wenlock Rocks.

$M_W = 57.15 \qquad \sigma_W = 5.49$

B Hawick Rocks.

$$M_H = 41.79 \qquad \sigma_H = 9.50$$

Southern Member:

$$M_{H1} = 50.5 \qquad \sigma_{H_1} = 4.13$$

Intermediate Member:

$$M_{H_2} = 34.6 \qquad \sigma_{H_2} = 5.99$$

Northern Member:

$$M_{H_3} = 43.5 \qquad \sigma_{H_3} = 8.34$$

C Garheugh Rocks.

$$M_G = 52.34 \qquad \sigma_G = 4.66$$

Again applying Student's "t" test, the difference between the Hawick and Wenlock Rocks was found to be highly significant, while that between the Hawick and Garheugh Rocks was significant at the 1% level. Further, the Southern and Intermediate Members of the Hawick Rocks were found to be significantly different, while the Intermediate and Northern Members differ at the 0.1% (highly significant) level.

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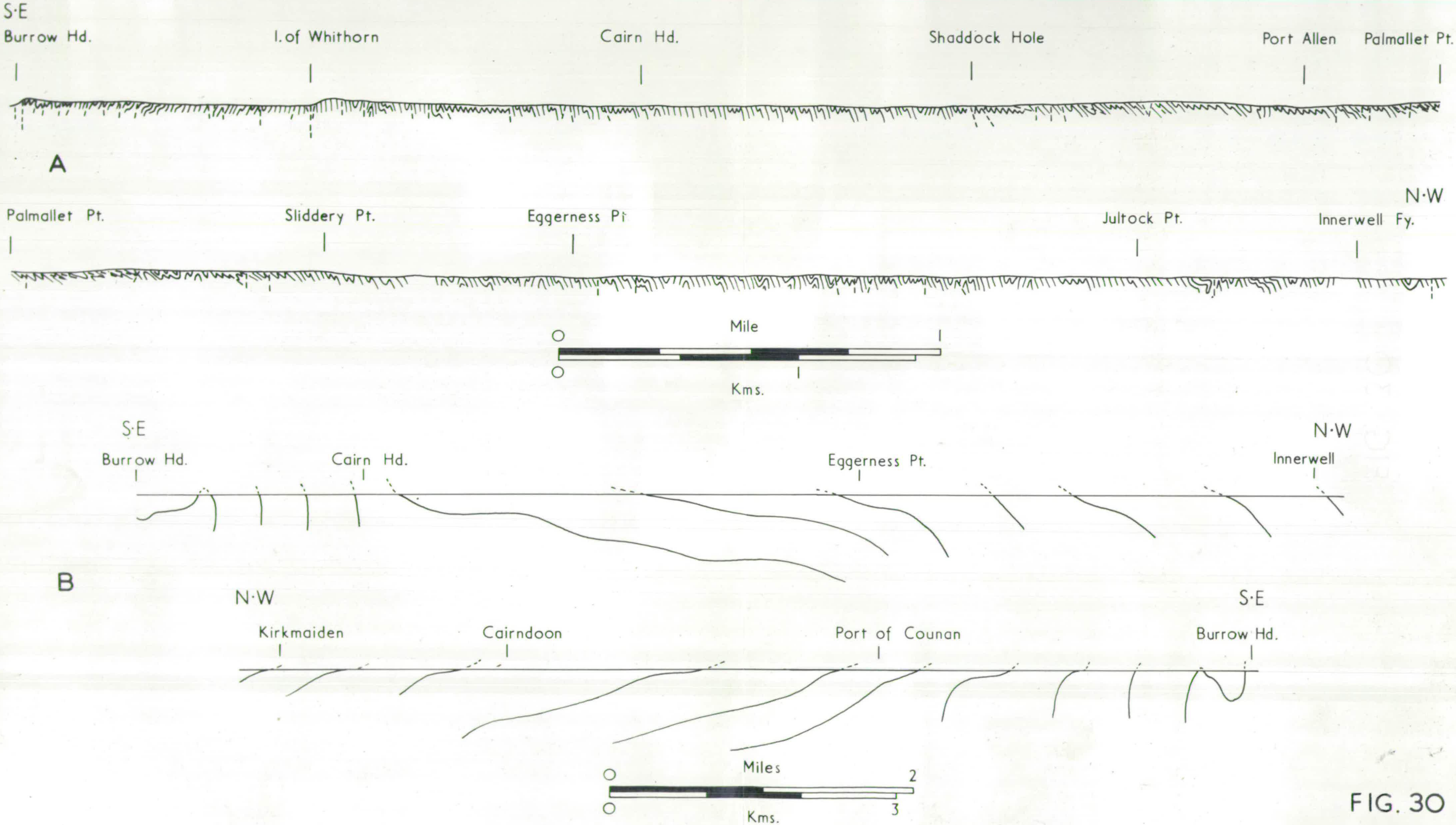
GEOLOGICAL MAP OF THE WHITHORN AREA, WIGTOWNSHIRE
LEGEND
DIP AND STRIKE : Uninverted beds
Probably uninverted beds
Inverted beds
Probably inverted beds
Cleavage and associated bedding
STRIKE OF VERTICAL BEDS : Arrow shows direction of upward sequence
... probable upward sequence
TREND AND PLUNGE OF FOLD AXES : F1
F2
F3
plunge < 90°
plunge > 90°
F4
F5
Where possible, dips and strikes of axial planes are also shown, e.g. (F1 axis)
HAWICK ROCKS
RICCARTON BEDS
SCALE
Miles
Kilometres
N
Orchardton
Innerwell Fishery
Jultock Point
Castle Head
SORBIE
GARLIESTON
Eggerness Point
Rigg Bay
Sliddery Point
Cruggleton Point
Palmallet Point
Port Allen
MONREITH
Craigenquor
Kirkmaiden
The Lag
Benbuie
Gray Mare's Tail
Cairndoon
WHITHORN
Shaddock Hole
Portyerrock Bay
Cairn Head
Carrickaboys
Stein Head
The Barns
ISLE OF WHITHORN
Port of Counan
Bloody Neuk
Physgill
LUCE BAY
Lobbocks
Carghidown
Devil's Arch
Mary Mine
Rock of Providence
Castle Feather
Stank
Broom Point
The Lick
Thief's Hole
BURROW HEAD



S·E
Burrow Hd.
I. of Whithorn
Cairn Hd.
Shaddock Hole
Port Allen
Palmallet Pt.
A
Palmallet Pt.
Sliddery Pt.
Eggerness Pt.
Jultock Pt.
Innerwell Fy.
N·W
Mile
0
1
0
1
Kms.
S·E
Burrow Hd.
Cairn Hd.
Eggerness Pt.
Innerwell
N·W
B
N·W
Kirkmaiden
Cairndoon
Port of Counan
Burrow Hd.
S·E
Miles
0
2
0
3
Kms.

FIG. 30